AquaMOOSE 3D:

A Constructionist Approach to Math Learning Motivated by Artistic Expression

A Thesis
Presented to
The Academic Faculty

by

Jason Lynn Elliott

In Partial Fulfillment
Of the Requirements for the Degree
Doctor of Philosophy in the
College of Computing

Georgia Institute of Technology
December 2005

AquaMOOSE 3D:
A Constructionist Approach to Math Learning Motivated by Artistic Expression

Approved by:

Dr. Amy Bruckman, Advisor
College of Computing
Georgia Institute of Technology

Dr. Janet Kolodner
College of Computing
Georgia Institute of Technology

Dr. Michael Eisenberg
Department of Computer Science
University of Colorado, Boulder

Dr. Elizabeth Mynatt
College of Computing
Georgia Institute of Technology

Dr. Mark Guzdial
College of Computing
Georgia Institute of Technology

Date Approved: August 22, 2005

This thesis is dedicated to my family. Without their love, support and encouragement, I would never have made it this far.

ACKNOWLEDGEMENTS

I would like to thank my parents, Jerry and Joyce Elliott, my brother Jerry Elliott, Jr., and my sister-in-law Sherry Elliott, for their unwavering support throughout the time I have spent at Georgia Tech.

I would also like to thank my wife, Jessica Paradise Elliott, who has kept me sane through these past few years. I hope I can return the favor.

This research would not have been possible without the guidance of my advisor, Amy Bruckman. She has stood by me throughout my career as a graduate student, and this thesis is as much a result of her commitment and persistence as it is of mine.

I would also like to thank the members of my thesis committee, Mike Eisenberg, Mark Guzdial, Janet Kolodner, and Beth Mynatt. Their contributions and compassion have inspired me and kept me going throughout the years.

Thanks also to my fellow graduate students, especially current and former members of the ELC Lab, who have provided endless support and truly made my experience much more enjoyable. I would also like to thank all of the other folks who have contributed to the AquaMOOSE project over the years. I am happy to say that there are too many such friends to name them all, but I would like to particularly thank Josh Berman, Jason Ellis, Rob Kooper, and Rodney Walker, who have continued to support and encourage me despite having moved on to bigger and better things themselves.

I would like to thank the GVU staff for all of their kind words and considerable help in making the processes run smoothly. I would also like to thank all of the students and teachers who participated in the AquaMOOSE project – it certainly would not have happened without them. Finally, I would like to thank the National Science Foundation, Microsoft, and Intel for their generous financial support of this research.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

SUMMARY

Research has shown that students' interest in academics declines significantly with age, especially in the areas of math and science (Kahle *et al.*, 1993; Wigfield, 1994; Wigfield & Eccles, 1992). One approach to combating this problem is by using new technologies to engage students who otherwise would not be interested in learning. In the AquaMOOSE project, we combine 3D graphical technology with a constructionist learning philosophy to create an environment where students can creatively explore new mathematical concepts.

The AquaMOOSE socio-technical system has been developed using an iterative design process. Three formal studies were conducted to assess the effectiveness of the system, as well as several smaller scale evaluations. The first study was conducted during a six-week summer program where students were able to use the AquaMOOSE system during their free time. The second study explored different learning issues in the context of a comparison-class study at a local high school where one section learned about polar coordinates using standard curriculum materials and an equivalent section learned the same material using a curriculum designed specifically around the AquaMOOSE system. The final study of the AquaMOOSE system was in an eight-week after-school program at a local high school where a balance between structure and creative freedom was explored.

In this thesis, I present the iterative design and evaluation of the AquaMOOSE socio-technical system. Evidence from this process is used to suggest implications of using 3D technology and constructionist philosophy for teaching complex mathematical content. The findings presented address issues of using constructionist learning environments for complex content and the tradeoffs of using 3D technology for educational systems.

CHAPTER I

INTRODUCTION

> *"In school math, 'analytic geometry' has become synonymous with the representation of curves by equations. As a result every educated person vaguely remembers that y=x^2 is the equation of a parabola. And although most parents have very little idea of why anyone should know this, they become indignant when their children do not. They assume that there must be a profound and objective reason known to those who better understand these things. Ironically, their mathophobia keeps most people from trying to examine those reasons more deeply and thus places them at the mercy of the self-appointed math specialists. Very few people ever suspect that the reason for what is included and what is not included in school math might be as crudely technological as the ease of production of parabolas with pencils! This is what could change most profoundly in a computer-rich world: The range of easily produced mathematical constructs will be vastly expanded (Papert, 1980)."*

One approach to doing educational technology research is to look at the current needs of teachers and students and design an intervention to meet those needs. In other words, doing "learner-centered design (LCD)" (Soloway *et al.*, 1994). Had we begun the AquaMOOSE project by interviewing teachers and students, we would no doubt have learned a great deal about their needs in these areas and designed a very different sort of math learning software. However, we consciously chose a different approach. This approach to designing educational software is to look not to the users' immediate practical needs, but to try to see the bigger picture: to discover ways in which new technologies can fundamentally help create new learning opportunities.

Technology and pedagogy led us to believe there was tremendous potential to facilitate new kinds of math learning. This was our starting point. Feedback from students and teachers was regularly incorporated throughout our design process; however, we began with broader reaching goals than meeting their immediate practical needs. Throughout the AquaMOOSE research project, we attempted to achieve a balance of both approaches. We began with a more radical “bigger picture” tactic trying to harness the power of new technology to make new kinds of math content appropriable, but simultaneously tried to make the system work within more traditional school contexts.

Underlying the design of the AquaMOOSE system is a philosophy of learning introduced by Seymour Papert called constructionism (Papert, 1980, 1991). Papert writes that learning, “happens especially felicitously when the learner is engaged in the construction of something external or at least shareable... a sand castle, a machine, a computer program, a book” (Papert, 1991). Furthermore, systems designed to support this type of learning experience should implement two major design principles: epistemological connections and personal connections. Resnick et al. summarize these guidelines:

> • *Personal connections*. Construction kits and activities should connect to users' interests, passions, and experiences. The point is not simply to make the activities more "motivating" (though that, of course, is important). When activities involve objects and actions that are familiar, users can leverage their previous knowledge, connecting new ideas to their pre-existing intuitions.
>
> • *Epistemological connections*. Construction kits and activities should connect to important domains of knowledge—and, more significantly, encourage new ways of thinking (and even new ways of thinking about thinking). A well-designed construction kit makes certain ideas and ways of thinking particularly salient, so

> that users are likely to connect with those ideas in a very natural way, in the process of designing and creating (Resnick *et al.*, 1996).

In the AquaMOOSE system, epistemological connections are provided through the software's ability to create visual representations of mathematical constructs. Students can *see* math in a new way. Imagine a student trying to understand topics like parametric equations and 3D polar coordinates aided only by traditional media like graph paper. These ideas are quite abstract and inaccessible. In the graphical 3D world, they are intuitive. Personal connections are facilitated by students' recognition of the 3D graphical technology used to create the AquaMOOSE software. In 2001, the massively multi-player online role-playing game EverQuest claimed to have over 400,000 subscribers (Verant, 2001). EverQuest players were playing an average of 22.4 hours per week to improve their characters and interact with other people from around the world (Yee, 2001). Since the success of EverQuest and other games, a slew of massively multiplayer online games have been released that appeal to even broader audiences. These entertainment environments demonstrate the appeal of 3D graphical worlds, especially for the target audience of the AquaMOOSE project: high school students.

One issue that is central to both personal and epistemological connections is maintaining students' interest. For constructionist environments to succeed, they must appeal to the users' prior interests as well as provide the users with opportunities to broaden their horizons and find new interests. Interest is a broad concept that is not fully understood. However, research has shown that student interest is also positively related to various measures of learning such as attention, comprehension, and thinking (Schiefele, 1991; Tobias, 1994). It has been shown that students' interest in academics declines significantly with age, especially in the areas of math and science (Kahle *et al.*, 1993; Wigfield, 1994; Wigfield & Eccles, 1992). Given the importance of getting students interested in learning, and the effectiveness of massively multi-player online games for engaging people in new activities, leveraging the appeal of this new technology to increase students' interest in learning seems to have great potential, especially for older students who have become uninterested in math and science.

Computers that are capable of supporting this new medium are becoming ubiquitous in schools. However, researchers and teachers are still searching for meaningful ways to use that technology to help students learn. In the AquaMOOSE project, we used an evolutionary socio-technical system design process to create a learning environment that could provide one solution to that problem. Socio-technical system design is an approach that integrates both the technical system and the social system in the environment (Ketchum & Trist, 1992). Interactions between participants, peers, mentors, teachers, and the technology are all equally important to the success of a socio-technical system designed for learning. Design research is a method of evaluating educational interventions by deploying systems into messy real world learning environments and then progressively refining the design of the system based on that feedback (Collins *et al.*, 2004). Combining these design methods has allowed us to adapt the AquaMOOSE system over the last seven years to meet our goal of making new mathematical constructs appropriable for learners.

This thesis presents the iterative design process of the AquaMOOSE 3D socio-technical system. The results from three large-scale formative evaluations of the system are described, as well as lessons learned throughout the seven-year development process. This chapter provides an overview of the AquaMOOSE research project and presents a summary of some core AquaMOOSE software features. The chapter concludes with an overview of the iterative system design and evaluation process that is presented throughout the remainder of this thesis.

1.1 Research Goals

The AquaMOOSE project aims to provide insights about two specific research areas. One area deals with supporting constructionist learning environments for complex subject areas, and the other addresses the affordances of 3D technology for teaching such complex subject matter. These two goals can be formulated as research questions:

- When the content that we want learners to learn using a constructionist software system is complex and very technical, what is needed in the supporting socio-technical system so as to engage the learners adequately?
- What are the tradeoffs in using 3D technology to support complex math learning?

Through many rounds of iterative design and formative evaluation, we have gained a better understanding of how to design a 3D constructionist learning environment for complex math and how that environment can be used in real-world settings. Our findings for both research questions can be summarized by the following main points:

- Art can be a useful way to engage students in complex math.
- Engagement varies among students and depends on a delicate balance between structure and freedom within the environment.
- Support for multiple paths to goal formation encourages engagement among a diverse set of learners.
- There is a mismatch between the complex math enabled by 3D technology and the math required in most standard school math curriculums.
- 3D technology facilitates visualizing complex math that is not possible to visualize with standard math tools.
- 3D technology can help promote personal connections to art.

Each of these findings resulted from evaluating students' use of the AquaMOOSE system in real-world settings. Evidence for these claims has been observed repeatedly throughout our iterative design and evaluation process. In Chapters III through VI, that evidence is reported through detailed accounts of our iterative design and formative evaluations. In the final chapter of this thesis, our research findings and supporting evidence are presented in greater detail.

1.2 Parametric Equations in 3D

Before developing the AquaMOOSE software, we first analyzed the affordances of the 3D graphical technology we wanted to leverage. Most 3D graphical virtual environments, including the successful online games mentioned earlier, involve users controlling avatars that move around in the environment. That user control can be represented mathematically by the path of the avatar's motion. In the AquaMOOSE software, we call such paths "mathematical trails." Parametric equations are a particularly useful mathematical tool for representing paths that objects travel through, so we implemented parametric avatar paths as the core feature of the AquaMOOSE software. Unlike the Logo programming language that uses first-person math to facilitate body-syntonic understanding (Papert, 1980), the AquaMOOSE software allows users to explicitly define parametric equations in a way that is similar to what they have seen in math classes at school. This similarity is intended to encourage students to build on the knowledge they have already seen in math classes so that they can apply that knowledge to the AquaMOOSE system.

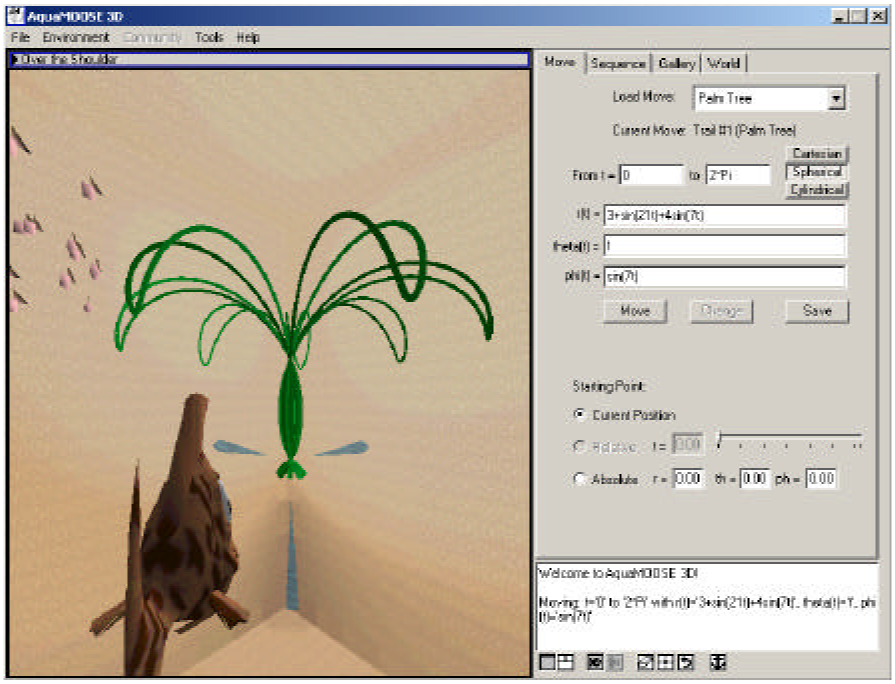


Figure 1.1: A math trail in the AquaMOOSE environment

Over the last seven years, the AquaMOOSE 3D software has been developed around that core feature using an iterative design process that involved many user trials (Elliott *et al.*, 2002; Elliott & Bruckman, 2002). The software consists primarily of a 3D graphical environment where the user is represented by a fish avatar. The avatar's motion can be specified mathematically by entering a set of parametric equations. Once users have created a mathematical "trail" by typing in parametric equations, they can manipulate the appearance and animation characteristics of that artifact (see Figure 1.1). Parametric equations allow users to create an unlimited number of visually appealing curves in 3D space that can express their ideas and creativity much like works of art. Throughout our iterative design process, we have continuously refined the opportunities for users to create personally meaningful artworks using parametric equations.

1.3 Participants

The AquaMOOSE system is designed primarily for high school students who have an interest in exploring new types of mathematics. This document describes several deployment studies where we evaluated the effectiveness of the system with different sets of high school students. Some students were participants in a summer program targeted specifically at gifted math students. Others were high school students taking required math classes in local schools. All of these students represent a wide range of ability, interest, and expertise that allowed us to explore the potential of the AquaMOOSE system.

In addition to high school students, we expect the AquaMOOSE system to appeal to math enthusiasts of any age. Our system is designed specifically for high school learners, but we have seen adults, teachers, and other researchers become engaged in the creative process AquaMOOSE supports. The diversity of artifacts that can be produced using the AquaMOOSE software is intriguing for many people, and we hope that all of those people may also benefit from using this research tool.

1.4 AquaMOOSE 3D Software Overview

The AquaMOOSE socio-technical system centers around a 3D graphical tool we created to provide an engaging context for students to explore mathematics. This section provides a brief overview of the most recent version of the AquaMOOSE software (see Figure 1.2) in the hopes of providing some context for the reader during the following chapters. The AquaMOOSE tool is available for download at http://www.cc.gatech.edu/elc/aquamoose. The design of the software tool is described in more detail in Chapters III through VI.

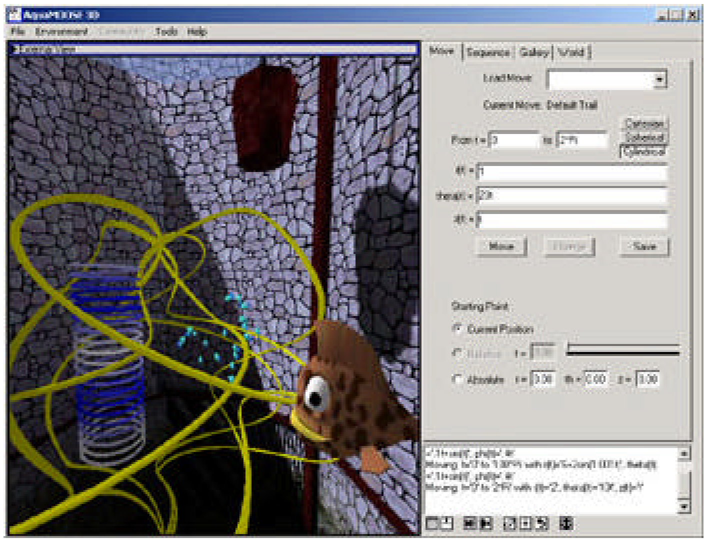


Figure 1.2: The AquaMOOSE 3D software tool

1.4.1 Conceptual Summary

The AquaMOOSE software is designed to support the creation of mathematical artifacts in a 3D graphical virtual space. The theme for that space is an underwater environment where users are represented by fish avatars. Fish avatars can swim around in the environment freely. They can also swim mathematically, however. When swimming mathematically, fish leave behind trails in the underwater environment that represent the 3D graphs of parametric equations (see Figure 1.3). Users enter 3D parametric equations to control their fish avatars' mathematical movements.

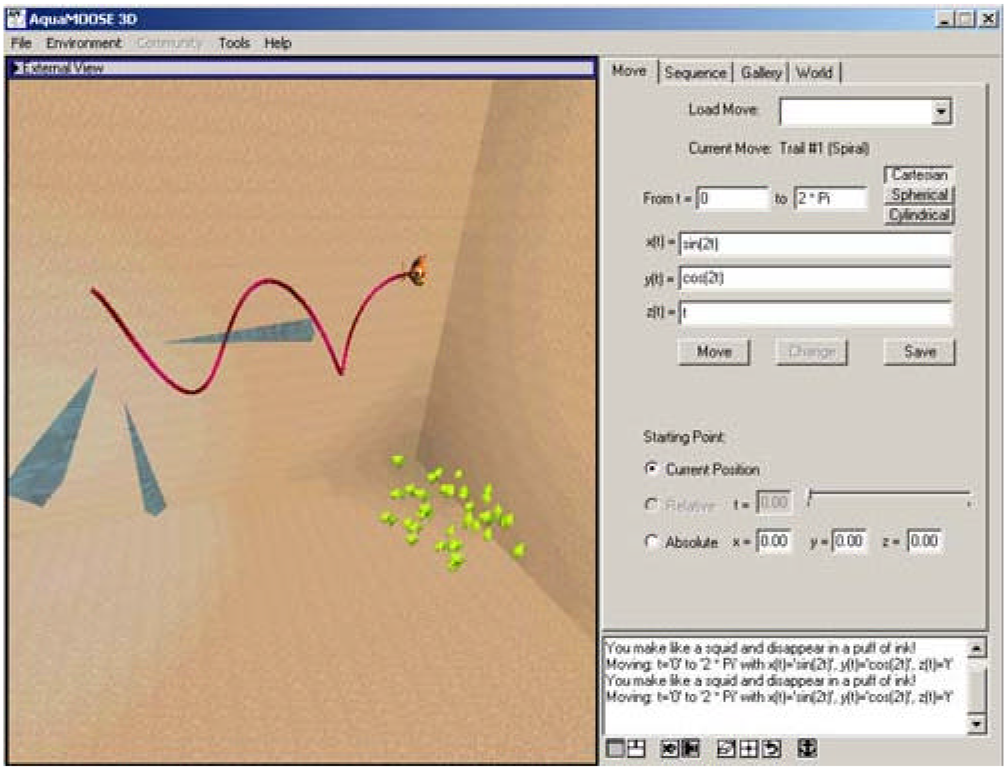


Figure 1.3: A mathematical trail in AquaMOOSE

Once users have created a trail by entering a set of parametric equations and having the fish traverse the associated 3D graph, they can directly manipulate the trail within the virtual environment. Presentation aspects, such as coloring and animation properties, can be altered. The mathematical equations used to create the trail can also be changed and then applied to the trail, morphing the artifact into a new representation of the modified equations. Users can create as many trails in the environment as they want, and they can place trails in relation to one another in order to create larger works of mathematical art. Mathematical trails can be saved in template form by saving its associated parametric equations or in scene form where the coloring, animation, positioning and camera configuration information is also recorded. Scenes allow users full control over how their mathematical artworks are presented (see Figure 1.4).

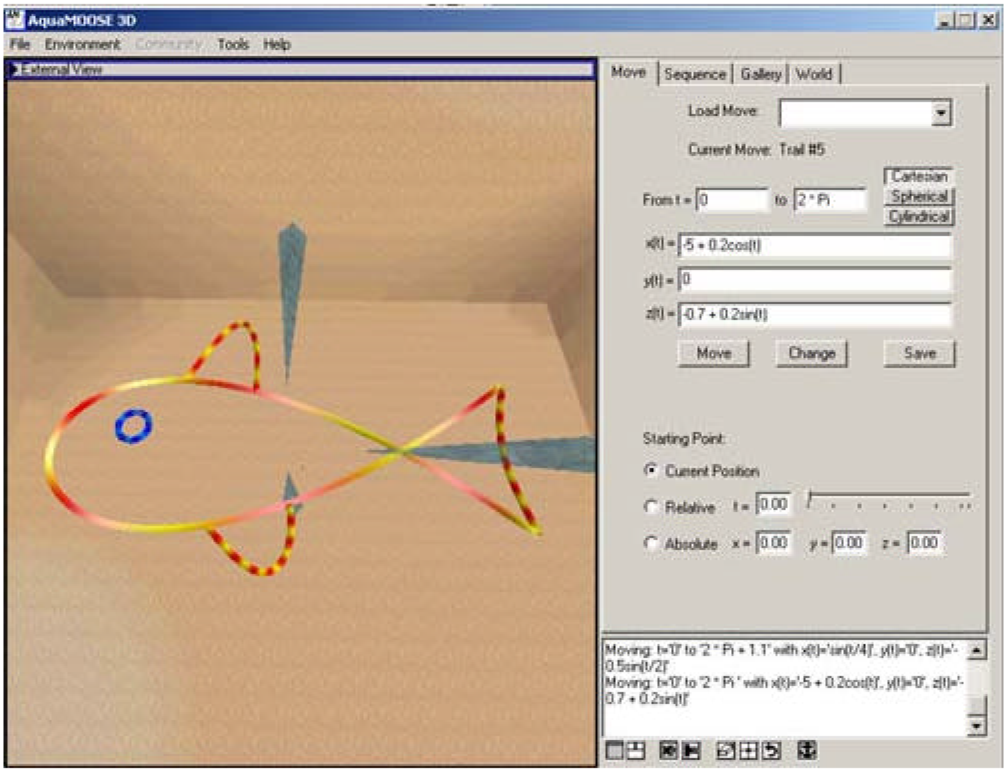


Figure 1.4: A scene in the AquaMOOSE environment

Artifacts saved in the AquaMOOSE environment can be shared with other users via a central server. Each user is given a public and a private folder. When a user wants to share an item with the rest of the community, he or she can simply drag the artifact into the public folder and it will become visible for anyone else to see. A browser interface allows users to see what artworks other people have made available and load them into the 3D virtual space. In addition to sharing artifacts through the built-in network, users have the option to record video clips of their artifacts that are generated by the software along with an animated preview of the video clip. This facilitates sharing AquaMOOSE creations on the web.

1.4.2 User Interface

This section provides some basic information about the user interface of the AquaMOOSE software tool. While it does not include all of the functionality supported in the tool, it presents the most common features that are referenced continuously throughout this thesis. The math interface is the core component of the system and is described first. The controls for navigating and manipulating trails are also presented, as well as the interface for sharing creations across the network and the antiquated interface for the ring game.

1.4.2.1 Math Move Interface

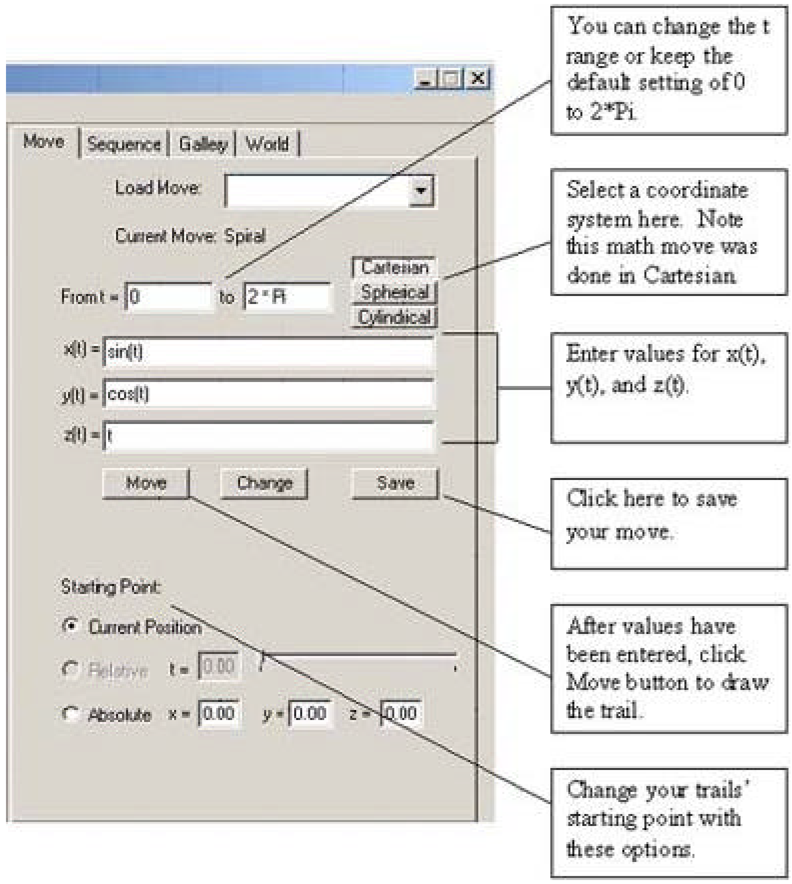


Figure 1.5: Math move interface

A simple template scaffolds the process of entering in sets of 3D parametric equations (see Figure 1.5). This template focuses on three input areas for the math equations, as well as areas to specify the beginning and ending parameter values through which the equations are to be evaluated. Users can also specify different coordinate spaces (Cartesian, cylindrical polar, or spherical polar) in which their equations should be evaluated, or choose to place their trail at a specific point in the 3D space using the “Starting Point” options.

1.4.2.2 Navigation and Layout

The fish avatar can be moved around in the AquaMOOSE environment using the mouse and keyboard. The arrow keys move the fish forward, backward, and from side to side. Holding down the X, Y, or Z keys on the keyboard moves the fish along the Cartesian x-, y-, and z-axes respectively. “Mouse look” mode is entered by holding down the right mouse button and allows users to freely rotate the fish avatar. While in mouse look mode, holding the left mouse button moves the fish forward and holding the middle mouse button moves the fish backward. Thus the fish can be moved entirely with one hand using the mouse, or with two hands by controlling rotation with the mouse and motion with the keyboard.

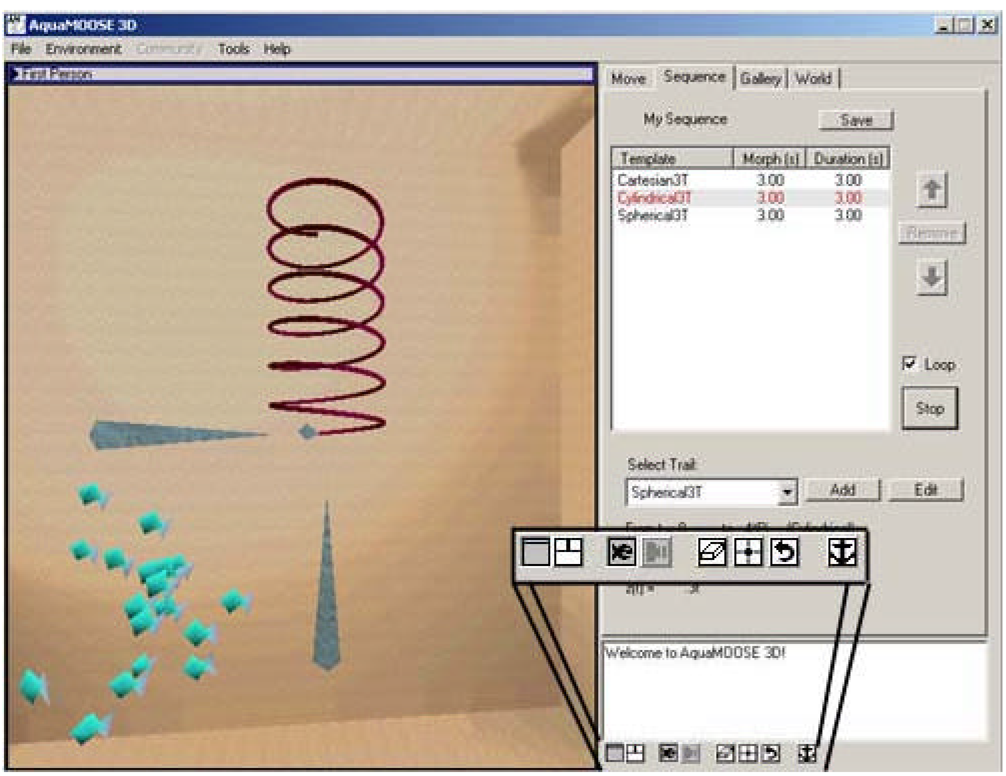


Figure 1.6: Shortcut buttons in the AquaMOOSE software

The AquaMOOSE software also provides features to control the layout of the user interface. Most of these functions are represented in menu items and in small shortcut buttons at the bottom right of the AquaMOOSE window (see Figure 1.6). Users can choose to show one view into the environment, or three separate views (two smaller and one larger). Each view into the world presents a specific camera, which the user can control. Five cameras are provided in the environment: a first-person camera inside the fish avatar's eyes, a side-view camera and an overhead camera that both center on the fish avatar, an over-the-shoulder camera that follows the avatar but is outside the fish's body, and a free-moving camera that can be controlled independently of the fish avatar. If the free-moving camera is visible in one of the views, the user can select whether their input should affect that camera or the avatar. This allows the free-moving camera to be placed in an environment such that it shows the fish avatar moving in a particular way. In addition to the camera and view options, shortcut buttons are provided to clear all trails in the environment, move the avatar back to the origin (in case the user gets stuck), and reset the environment.

1.4.2.3 The Gallery

Each user is given a "Private" and a "Public" folder when they join the AquaMOOSE system. Artifacts are saved to the private folder initially, but can be moved to the public folder via an interface called the "Gallery" (see Figure 1.7). The gallery also provides a browser through which users can view other people's public creations. Right-clicking on any of the items in the gallery also displays a context menu with relevant actions based on the type of item selected. Selecting another online user provides the option to begin an instant messaging session with that user, for example.

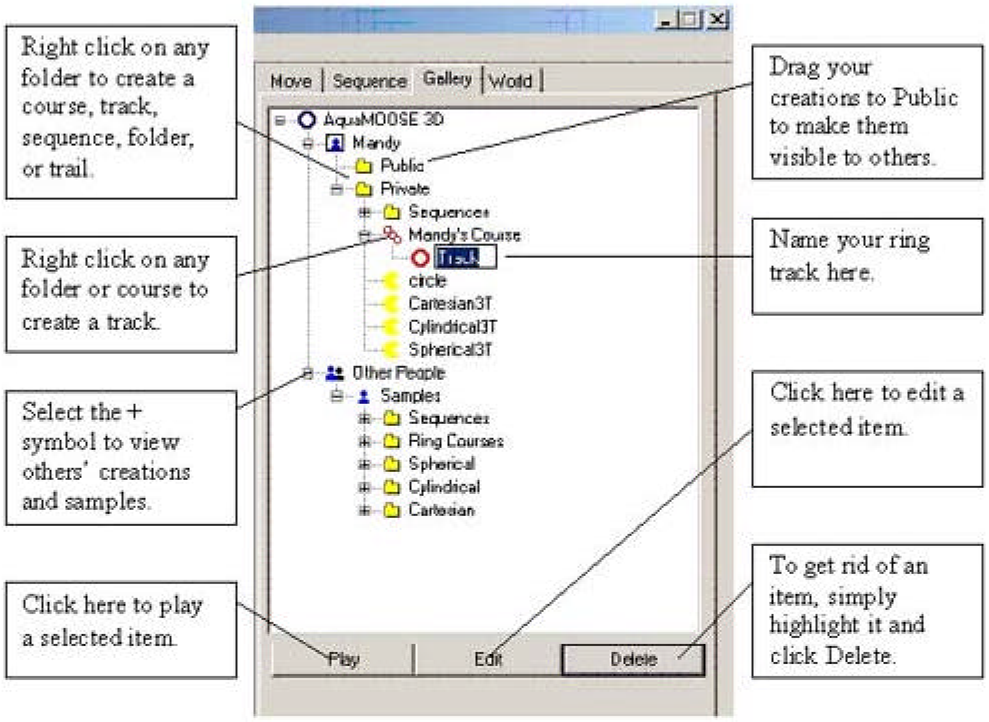


Figure 1.7: The AquaMOOSE gallery interface

1.4.2.4 The Ring Game

The Ring Game consists of multiple series of rings laid out in the 3D space according to sets of parametric equations (see Figure 1.8). The objective of the game is to move the fish avatar through all the rings in one math move. Many ring layouts can be combined into a ring course, similar to the idea of a golf course. Users can create ring tracks and courses, refine them, and then challenge their friends to complete the ring courses. Ring courses can be played directly from another user's folder in order to keep the underlying equations hidden, or they can be copied to allow editing and manipulation. The Ring Game was inspired by Sharon Dugdale's "Green Globs" software that used 2D polynomial equations to intersect with randomly placed dots on a graph (see Section 2.5.5).

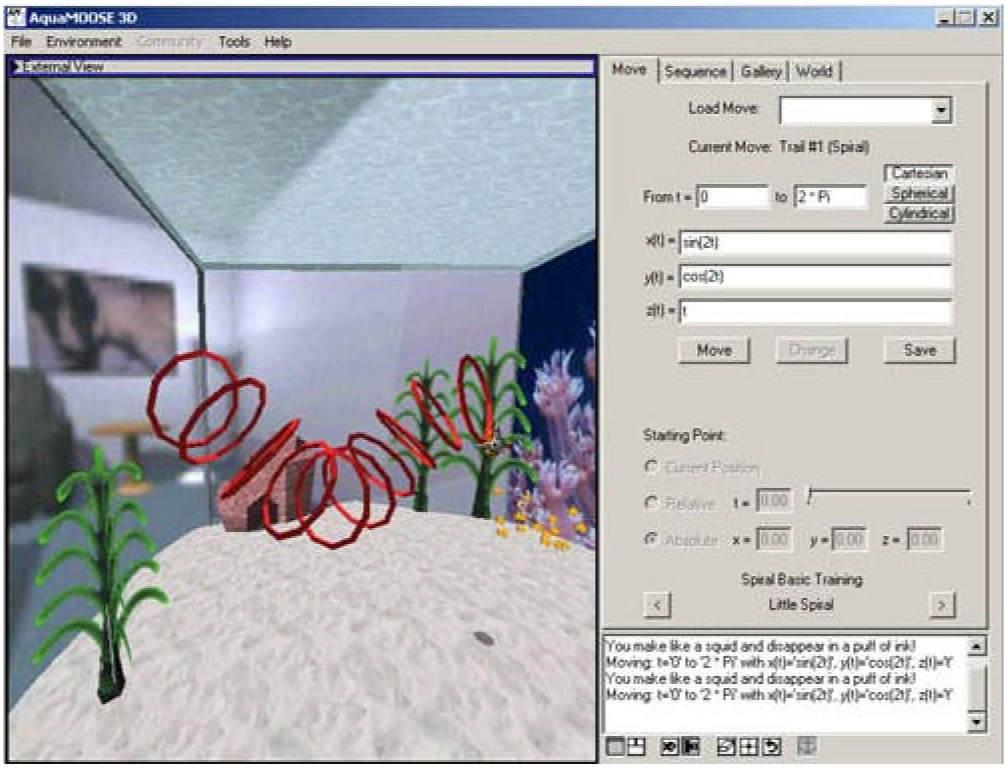


Figure 1.8: The Ring Game

In our deployment studies, students had difficulty designing ring courses that provided an appropriate challenge for others. It was easy for them to use complicated math to create nearly unsolvable ring courses, but hard to create ring courses that were solvable and challenging. This result is discussed in further detail in Section 4.5. As a result of this finding, the ring game was disabled for the final evaluation of the AquaMOOSE system, and it remains disabled in the current version of the software.

1.5 Thesis Overview

We have completed three major deployments and several smaller feedback evaluations of the AquaMOOSE system. Early evaluations gave invaluable feedback about usability and system design that helped the AquaMOOSE system evolve. Details about all of the AquaMOOSE deployments and evaluations are shown in Table 1.1.

Table 1.1: Details of AquaMOOSE deployments and evaluations

Date	Participants
Winter 2000	Small group of college freshmen
Spring 2001	Advanced math class from Atwood Private School
Spring 2001	Students from Georgia Tech
Spring 2001	Six local high school math teachers
Summer 2001	Georgia Governor's Honors Program
Fall 2001	Math club at Brooks High School (public)
Fall 2001	Advanced math class from Atwood Private School
Spring 2002	Two pre-calculus classes at Brooks High School
Spring 2004	High school students at Thompson High School

The first trial of AquaMOOSE was for a formative evaluation we conducted with a small group of college freshman who used the AquaMOOSE software in a laboratory session in late 2000. We observed that co-location was an important aspect of the learning process. Students looked over one another's shoulders sharing excitement about their creations and trading mathematical strategies.

For our second trial in Spring 2001, we invited a small advanced math class from a local private high school, which we will call Atwood Private School[1], to evaluate the software in our laboratory. One student in that class, Joel, completed an entire ring course (see Section 1.4.2.4) in about 15 minutes, whereas his classmates and teacher took nearly an hour. On approaching the system, Joel immediately understood exactly what to do, and he solved the first segment of the first puzzle in seconds. We were surprised to see such a large range in achievement within an honors class. Based on conversations with Joel and his teacher, we believe his success was attributable to his unusually well developed skill in both mathematics and visualization. Joel was

[1] All school and student names throughout this document have been altered to protect the participants' privacy.

energized by his experience, and he continued to explore the system avidly while his classmates finished their work. We refined the system's visualization supports to try to make it as immediately accessible to others as it was to Joel.

We then conducted several rounds of formative evaluation with other students at Georgia Tech. The results from these multiple rounds of formative evaluation helped shape the system's design and user interface.

In addition to our testing with students, we invited six local math teachers to talk with us about AquaMOOSE and how it might be used in their classes. Based on those conversations, we developed a better idea of how to integrate the application with a pre-calculus curriculum.

During the summer of 2001, we conducted our largest deployment with 105 high school math students at the Georgia Governor's Honors Program. This study was designed primarily to get general feedback from students about the usability and feasibility of the AquaMOOSE system. The participants were introduced to the software and then were allowed to use it however they wished during their free time (see Chapter IV).

Our next trial was in fall 2001 with an after school math club at a local public high school, which we will call Brooks High School (BHS). The purpose of this trial, in addition to obtaining more usability feedback from the students, was to demonstrate the software to the math teachers at BHS in preparation for a larger deployment. Brooks High School is in a relatively impoverished suburb of Atlanta, Georgia. The majority of the students qualify for free or reduced lunch, which is an indicator of socio-economic status. The students at BHS enjoyed playing with our software, but they were distracted by the informal atmosphere of the math club. Their club meetings were normally a place where people came to hang out and chat about various math-related activities; they were not accustomed to sitting down together formally. The math teachers at BHS were impressed by the AquaMOOSE system and were excited about the possibility of a larger-scale deployment in some of their classrooms.

Also in fall 2001, we conducted a trial with another advanced math class from Atwood Private School to gain more usability feedback about the AquaMOOSE software. The private school students were able to carry on involved conversations with us about the concepts in the AquaMOOSE software. This particular class had already covered one of the most difficult concepts in our software, 3D polar coordinate space (spherical polar coordinates), and the students were engaged by the process of exploring that concept further in the AquaMOOSE software.

We then did a comparison class study at a suburban high school in early 2002, where we compared the AquaMOOSE intervention to instruction using the traditional curriculum at Brooks High School. The comparison class learned about polar coordinate space using the standard curriculum guide and materials, while the experimental class used a curriculum that we designed around the AquaMOOSE software. The results from this deployment gave us insights about refining our socio-technical system to support constructionist learning activities (see Chapter V).

The final deployment of the AquaMOOSE socio-technical system was in an after-school program at another local high school, which we will call Thompson High School (THS). In this study, we combined the lessons learned from the previous evaluations to create a semi-structured environment where participants were challenged to create portfolios of mathematical artworks to share with their friends and family. In this deployment, we studied the AquaMOOSE socio-technical system with two goals: understanding how to better support constructionist learning of complex content and describing some of the trade-offs involved in creating such a system using 3D technology (see Chapter VI).

In the next chapter, the theoretical foundations of the AquaMOOSE project are presented, as well as related research projects that have influenced the design of the AquaMOOSE system. Chapter III presents lessons learned from the early prototype stages of the AquaMOOSE project. In Chapter IV, the Governor's Honors Program study is presented in greater detail. Chapters V and VI describe the other two major evaluations, the BHS classroom study and the MHS after-school program. The final chapter of the thesis summarizes the lessons learned throughout the AquaMOOSE project and how those lessons might inform a further research agenda.

CHAPTER II

BACKGROUND

This chapter provides information about the theoretical foundations of the AquaMOOSE project as well as some other related research projects. The AquaMOOSE environment is a socio-technical system, developed over a period of seven years using an evolutionary design process, which explores the potential of combining 3D graphical virtual worlds with constructionist philosophy to create new and engaging math learning experiences. The chapter begins with a discussion of each of the core components of the AquaMOOSE project: constructionism, interest and learning, socio-technical system design, and evolutionary design.

2.1 Constructionism

In traditional classrooms, students are expected to receive information relayed by the teacher, absorb it, and come to understand it in the same way that the teacher understands it. This is often called the transmission model of learning. An alternative model recognizes the critical role that social interaction plays in the learning process (Newman *et al.*, 1989; Wertsch, 1986). Constructionism, which is an extension of Jean Piaget's constructivism (Piaget, 1972), theorizes that people learn better through building personally meaningful artifacts and sharing them with others (Bruckman, 1998; Papert, 1991). Constructionism is the main educational philosophy underlying the design of the AquaMOOSE system.

One important aspect of a constructionist learning environment is audience. Students learn more effectively when they are creating artifacts that will be viewed and commented on by other people. In the ISDP Project, fifth grade students helped fourth grade students design software tools to teach fractions to third graders (Kafai & Harel, 1991). The fifth grade students benefited greatly from having a novel audience to share their ideas with during consultation sessions. They were more willing to explain their theories about fractions to younger students who had less experience and knowledge about the topic than to other fifth graders or a teacher. Other research has also shown that audience is an important factor for engaging students in a constructionist learning process (Zagal & Bruckman, 2005).

The AquaMOOSE system is designed to provide an audience by supporting users sharing and discussing each other's mathematical creations. Participants can build objects in their "private" space, and then simply move them to their "public" space when they feel comfortable sharing them with the rest of the AquaMOOSE community. Participants throughout the project's evolution could also utilize the social aspects of the system, such as advisory sessions, critiques, and physical collocation, to get feedback from peers, teachers, and mentors at various stages of their learning process. The final objective of the after school program we conducted most recently was for participants to create a portfolio of objects that were presented to a local audience of friends and family. This presentation was an important motivating factor for the participants throughout the program (see Chapter VI).

Constructionism also emphasizes the need for learning activities to incorporate both personal and epistemological connections (Resnick et al., 1996). Personal connections allow users to build on previous knowledge about particular topics that they are already interested in, while epistemological connections encourage users to explore new ways of thinking about their previous knowledge and their understanding of the underlying concepts. In the StarLOGO project, for example, students can imagine themselves as an individual participant in a complex decentralized system, which allows them to make a personal connection with the content material while also exploring an entirely new way of thinking about real-world phenomena (Resnick et al., 1996). Similarly, the SchemePaint tool attempts to balance personal and epistemological connections by allowing students to have creative flexibility while also exploring how to think about using mathematics for artistic expression. Students can create projects that combine “mouse-drawn” components from the friendly direct manipulation interface with code-generated components from the graphics-enhanced Scheme interpreter (Eisenberg, 1995). Supporting both of these modes of artistic expression greatly increases the range of artifacts students can create using the SchemePaint tool.

In the AquaMOOSE system, participants make personal connections through the visual appeal of the mathematical trails and animations. They are often familiar with similar graphical effects from other settings, such as video games and movies, and are engaged by the possibility of creating such effects themselves. Complex combinations of mathematical concepts, used in novel ways, lay the foundation for students’ epistemological connections. Students are not often taught in school that math can be used to make intricate graphical designs, and like the SchemePaint tool, the AquaMOOSE environment gives them the ability to freely explore those possibilities by building on their prior math knowledge. By participating in the AquaMOOSE system, students can build interesting visual objects that combine their imagination with mathematical concepts to create beautiful and elegant works of personally meaningful mathematical art.

Another issue that plays a critical role in the success of constructionist learning environments is the amount of structure that surrounds the learning activity. On one hand, researchers have developed problem- and project-based learning environments where students are provided with learning-appropriate goals and scaffolds to help them progress through the learning activity (Barron *et al.*, 1998). On the other hand are more open-ended radical constructionist environments, such as the Friskolen 70 school in Denmark, where students are not given any specific learning requirements and are expected to control their own learning experience using materials available in the environment (Falbel, 1989).

In the AquaMOOSE project, we have explored a range of structure and student control characteristics and have examined the results from using our system at three different points along the problem-based to radical constructionist spectrum (see Chapters IV, V, and VI). Our experience has indicated that the AquaMOOSE system is best suited to a moderate point in the the spectrum where students are given some structure and guidance about the learning process, but are also encouraged to explore personally meaningful avenues within that structure. For example, in the after-school program we conducted, students were given the broad goal of preparing a portfolio of mathematical artwork to share with an audience of friends and family. They were encouraged to create any mathematical artifacts that they thought were appealing. To help the students get started, however, we also provided them with smaller goals that they could choose to work on as well but were not required to complete (see Section 6.1.3.4). This combination of creative freedom and small, optional goals allowed the participants to create a wide range of aesthetically appealing mathematical artworks (see Section 6.1.4).

2.2 Interest and Learning

The term "interest" is often used interchangeably with the term "motivation." However, in the motivation literature, interest is usually described as just one factor that influences motivation. Motivation is defined as "the process whereby goal-directed activity is instigated and sustained (Pintrich & Schunk, 1996)." When laypeople are asked to define motivation, however, they often describe it in terms of a person's interest in performing some task or activity. This definition of motivation emphasizes the enjoyment a person gains from doing a task or their subjective interest in the content of a task (Wigfield & Eccles, 1992). For the purposes of this research, we refer to interest as an internal state that causally impacts students' attention, learning, thinking, and performance. It is this construct that we attempt to influence with the AquaMOOSE socio-technical system.

There are two different types of motivating factors that can influence learners' engagement and interest in a particular activity. Extrinsic motivators are external results of performing a particular activity that are desirable to the participant, such as a physical reward, praise from a teacher, or avoidance of punishment. Intrinsic motivation does not rely on external outcomes, but instead reflects a willingness to engage in the activity for its own sake (Pintrich & Schunk, 1996). In the AquaMOOSE system, we try to foster intrinsic motivation by giving students more control over their learning experience rather than depending on external outcomes. Peer feedback and positive encouragement from an audience are still important components of the AquaMOOSE system, but the emphasis of the learning activity is on the students' individual investment in their personally meaningful creative endeavors.

During extended learning experiences, interest has been shown to wax and wane based on the activities students are engaged in at a particular stage of the learning process (Joseph & Nacu, 2003). Joseph and Nacu propose that learning environments should incorporate strategies for sustaining interest throughout the learning intervention. Specifically, they suggest that support should be addressed during both the initiation and maintenance stages. Initiation strategies involve introducing activities that are designed to direct students' attention to a particular topic that might be interesting. Maintenance strategies involve using context-based supports such as deadlines or social motivators to help boost interest levels during the times when interest is expected to wane. In the AquaMOOSE system, we designed activities specifically to address these concerns. For example, throughout our system we provided participants with "challenges" that were intended to help initiate interest in specific concepts. We also included specific deadlines, such as critique sessions, to help motivate students at the point of the learning experience when we expected their interest to wane.

2.3 Socio-technical Systems

Socio-technical system theory proposes that organizations are comprised of two independent, but interconnected, systems: a technical system and a social system. The technical system involves technology and processes, while the social system involves people and social practices (Ketchum & Trist, 1992). The technical system includes computers, computer software, and other inanimate objects such as pencils and calculators. The social system includes interdependencies between the actions of multiple persons, including "communication and cooperation structures, formal organizational structures, personal expectations and interest or qualifications (Herrmann & Loser, 1999)."

We have seen in our past work that deploying the AquaMOOSE software with a stronger emphasis on the technical system than the social system often does not achieve the expected results (see Chapter IV and Chapter V). In our most recent implementation, we developed an educational intervention that emphasized both the technical system and the social system. The AquaMOOSE software remained a key component to the goals of the research, but the curriculum design, social interactions, feedback mechanisms, and audience aspects were also critical to the effectiveness of the intervention. Each of these components was carefully designed and is an integral part of the AquaMOOSE socio-technical system.

2.4 Design Research

Conducting design experiments, more recently referred to as design research, is a relatively new method for examining the impacts of educational interventions that stemmed from previous ideas about doing design experiments (Brown, 1992; Collins, 1992). Design research is a method that supports testing and refining educational designs over a period of time based on the results of previous formative evaluations. For education research, laboratory studies are unable to capture the true effects of an intervention. Design research assesses the effects of experimental systems within the messy context of real-world learning environments(Barab & Squire, 2004; Collins et al., 2004; Fishman *et al.*, 2004). That assessment then feeds into the design of a new iteration of those experimental systems.

There are three common approaches to designing systems to support educational activity. Technology-centered design looks at the affordances of a technology and attempts to design a system that makes the best use of that technology (Elliott & Bruckman, 2002). User-centered design begins instead by understanding users' needs and designing a system to support those needs (Norman & Draper, 1986). In short, the user is at the center of the design process rather than the technology. Learner-centered design is an extension of user-centered design where the focus is on supporting learning processes rather than general tasks (Soloway et al., 1994). Supporting learners rather than general users means designing systems that promote understanding, encourage motivation, and facilitate intellectual growth.

In the AquaMOOSE project, we have combined all of these design methods to explore how 3D graphical technology can make new math learning activities possible. We began with the technology, attempting to understand its properties and affordances. We designed a system that took advantage of those characteristics. Then we deployed the system in several rounds of formative evaluation using different learning contexts. Feedback from the learners in those evaluations fed into an iterative design process where we continued to adapt our system to better support the learning activity. Once we had some initial descriptions of how learners used the AquaMOOSE system, we were able to carefully consider their needs and design new features to support those needs. Collins, et al. describe this process: "This approach of progressive refinement in design involves putting a first version of a design into the world to see how it works. Then, the design is constantly revised based on experience, until all the bugs are worked out (Collins et al., 2004)." This process has allowed us to closely examine the potential of the AquaMOOSE system across different settings.

2.5 Related Work

Several research projects have influenced the AquaMOOSE system in various ways over the last seven years. Some gave insight into features that might be useful in the AquaMOOSE software, while others provided examples of how to structure the social context of the system to promote learning. Though other projects have also been important for the development of the research ideas in the AquaMOOSE system, seven particularly relevant projects are highlighted in this section: MOOSE Crossing, LBD, Hypergami, Logo, Green Globs, Alice, and ISDP.

2.5.1 MOOSE Crossing

MOOSE Crossing is a text-based online community designed to support children learning about creative writing and object-oriented computer programmming (Bruckman, 1998; Bruckman & Edwards, 1999). MOOSE includes a scripting language that uses natural-language type syntax to allow kids between 8 and 12 years of age to easily access and learn common programming constructs. MOOSE Crossing demonstrates how the Internet can allow people to learn by creating and sharing personally meaningful objects in a virtual setting (Resnick et al., 1996). MOOSE users create objects such as pet dogs that follow them around, swimming pools where groups can gather for parties, and shopping malls where others can browse through various creations.

MOOSE Crossing shows that students can become engaged in sharing and discussing their ideas and creations over a computer network (Bruckman, 1998). This is another mode of interaction that we have designed into the AquaMOOSE system. Although participants in the evaluations we conducted were collocated, they were also able to use the AquaMOOSE software from home or other settings via the network component (see Section 1.4.2.3). This allowed students to continuously share their work and give each other feedback throughout the duration of the program, sustaining the presence and motivational impact of an audience of peers.

2.5.2 Learning By Design (LBD)

Learning by Design is an approach to middle-school science education that uses design challenges to teach students about design practices and skills in addition to more traditional science content (Kolodner, 2002; Kolodner *et al.*, 2003; Kolodner *et al.*, 1998). One of the main strategies of LBD is to engage students in an iterative cycle of activities that bring the content and practices to the foreground of the students' attention. Part of this cycle involves students freely exploring the design space, engaging in more structured activities that test and provide feedback on what was learned during exploration, and then reflecting on what they learned and how that knowledge can be effective in other situations.

This process of informal exploration followed by feedback and reflection is an important part of the AquaMOOSE socio-technical system design. Participants in the AquaMOOSE system begin by exploring the supported design space of mathematical art, similar to the ritual practice in LBD of "messing about." Messing about allows students to formulate their own questions and interests before going deeper to try to understand the underlying concepts. After participants have generated some questions or goals in the AquaMOOSE system, they refine the math they are using and receive feedback from others through activities like advisory sessions, formal critique sessions, or informal interactions. These activities are similar to LBD's public presentation rituals: poster sessions, pin-up sessions, and gallery walks. Once an artifact has been completed, AquaMOOSE participants have the option to provide a written artifact description that contains information about the purpose of the object and the process of creating it. This reflective activity gives the students a chance to carefully think about and explain the knowledge they have gained through designing and creating each of their artifacts. These artifact descriptions can then be referenced as the participants create more artifacts, prompting the students to incorporate past experiences into their new explorations and designs.

2.5.3 SchemePaint and Hypergami

SchemePaint is a tool created by Michael Eisenberg that allows students to create digital artworks by using a friendly graphical direct manipulation interface, by writing scripts using a graphics-enriched version of the Scheme programming language, or by combining both modes (Eisenberg, 1995). SchemePaint attempts to make writing computer programs more accessible to a broader audience, rather than restricting the power of such activities to a limited population of computer experts. SchemePaint users can use this dual mode of interaction to create amazing works of art by combining their artistic creativity with their understanding of programming and mathematics.

Similarly, Hypergami is another software tool created by Michael and Ann Eisenberg to allow students to explore the creation of 3D polyhedral models using both direct manipulation interfaces and computer programs (Eisenberg & Nishioka, 1997). The software generates 2D nets of 3D polyhedral structures, which can then be printed out on paper and folded back into the 3D model. The software supports manipulating and decorating the 2D nets with standard paint tools as well as a programming language that is similar to Logo. Hypergami also supports the creation of "ori-hedra," or sets of 3D polyhedral models that can be combined to create more complex works of mathematical art.

In the AquaMOOSE system, participants construct 3D artifacts that combine math equations with artistic goals. Like SchemePaint and Hypergami, we attempt to give students the flexibility to pursue creative artistic endeavors while building on and expanding their understanding of the underlying mathematical concepts. Though the AquaMOOSE system's direct manipulation and programming interfaces are more narrowly scoped than those in SchemePaint and Hypergami, students throughout the AquaMOOSE evaluations have created numerous visually appealing artifacts that demonstrate the potential of this type of application for supporting a rich and meaningful learning experience.

2.5.4 Logo

In the LOGO environment, users can write programs to control a cursor on the computer screen. The process of moving the cursor (the "turtle") around on the screen generates drawings that are referred to as "turtle graphics." For example, a simple LOGO program might consist of the commands, "pen down; move forward 100." This would draw a straight line 100 units on the screen.

This process resembles the way math trails are created in the AquaMOOSE environment. People who see demonstrations of the AquaMOOSE software often refer to the trails as "LOGO in 3D." However, we incorporated a different strategy in our design of the AquaMOOSE math trails. While the math in Logo is done from a first-person perspective to facilitate body-syntonic understanding of math (Papert, 1980), the math in AquaMOOSE is designed to look more like the math students see in school in order to facilitate transfer.

LOGO has been used in many different forms and contexts over the last two decades, but each instantiation focuses primarily on allowing people to use computer technology to create artifacts that leverage their personal interests while providing them with greater insight and understanding of the underlying mathematical constructs. This is the approach we have taken in designing the AquaMOOSE socio-technical system: to provide students with an interesting way to create personally meaningful artifacts while gaining a better understanding and appreciation of math and art.

2.5.5 Green Globs

The Green Globs software is a software tool that uses simple 2D graphics-based games to teach high school students about algebra (see Figure 2.1). Students are presented with a screen containing several dots, or "globs", that are randomly placed on a grid. Their goal is to make "shots" using polynomial algebraic equations that will hit as many of the globs as possible, and take out all of the globs in the fewest number of shots. The children using the Green Globs software were motivated by the game scenario and were led to explore many complex algebraic solutions that they would not have been exposed to otherwise (Dugdale, 1982).

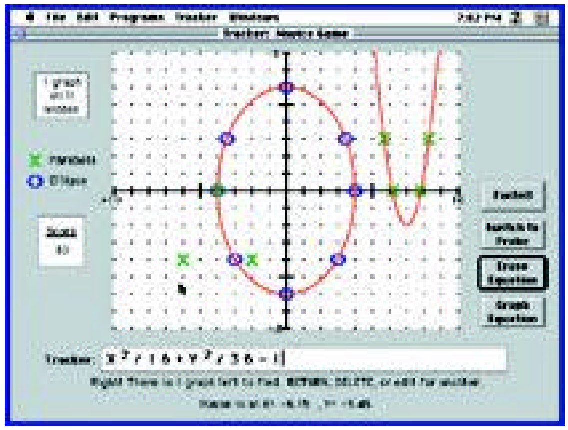


Figure 2.1: Green Globs software interface

In designing the Green Globs software, Dugdale and colleagues made some interesting design decisions to provide an appropriate level of motivation for students to explore new types of algebraic concepts. One contribution was to devise a feedback system that gave students of various mathematical abilities an equal feeling of accomplishment and desire to improve their problem-solving strategies. Scoring in green globs was originally done by counting the number of shots it took a student to burst all 13 globs. The problem with this arrangement is that most students could burst all of the globs easily in 6 shots, but it took an extremely favorable layout of globs to do so in less than 4 shots. With such a small range of possible scores (4 to 6), there was little motivation for students to improve their approach to constructing equations. The scoring algorithm was then changed to provide more points for each consecutive glob hit with a single shot. So the first glob would score 1 point, the second 2, the third 4, the fourth 8, and so on. With the new scoring algorithm, Dugdale found students of varying math skill were equally interested in improving their equations to score more points.

Another contribution of the Green Globs project was Dugdale's recognition and encouragement of creative exploration in academic tools. Students using Green Globs devised many creative methods for bursting large numbers of globs in a single shot. For example, students learned to use factors of the form (x – a) along with large coefficients to create nearly vertical lines on the graph. Combining several of those factors allowed students to hit many of the globs with a single equation. This type of creative solution is something that students would not normally internalize based simply on classroom exposure. In the Green Globs environment, however, students were motivated to understand and use concepts that would otherwise be just another homework assignment. Green Globs was also designed to encourage students to explore algebra freely, without being constrained to the specific graphs or concepts they are studying in math class.

The Green Globs project inspired the creation of the AquaMOOSE game space called the Ring Game (see Section 1.4.2.4). In the Ring Game, students create a sequence of rings using mathematical equations and then challenge their friends to solve their ring puzzles. As in Green Globs, the students do not have to guess the exact math equations, since the rings have a large diameter and passing through any point within the ring is sufficient. However, this game turned out to be too difficult for students to use, due mainly to the added difficulty of the third dimension (Elliott et al., 2002). Given the limitations of the Ring Game, we have focused on different mechanisms to support the type of motivation that the competitive game provided in Green Globs.

Green Globs serves as a positive example of educational technology that increases student interest through creative exploration of complex mathematics. Students are allowed to try out different math concepts at their own pace in a playful setting. Even though the students are often motivated by competition to score more points, the system was designed so that students at various ability levels can improve and feel successful in their explorations. The AquaMOOSE socio-technical system aims to provide a similar opportunity for students to become more interested in math and art through the process of creating personally meaningful mathematical artworks.

2.5.6 Alice

The Alice project was created to make it easier for a wide audience of users to interactively create 3D graphical content (Conway *et al.*, 2000). A set of authoring tools were created that allowed users to design and implement 3D graphical animations using a graphical interface and a scripting language. The interface and scripting language in the Alice software were developed iteratively to appeal to a broad audience of non-science/engineering users. Alice removed many of the complicated mathematical constructs from 3D animation, such as absolute coordinate axes and transformation matrices.

In the early stages of the AquaMOOSE project, we used the Alice software as a prototyping tool (see Section 3.2). We were able to use the Alice system to further explore the feasibility of using 3D graphical systems to support students learning about new mathematical concepts. Many of the ideas that the Alice software incorporated to address usability concerns were integrated into the AquaMOOSE software as well. Alice included shortcuts that were designed to make navigation and creation in a 3D environment more intuitive for non-technical users. Based on early informal user studies and our experiences with the Alice prototype, we developed features such as dropping anchors and jumping to a safe spot in the 3D space to address similar usability issues.

2.5.7 Instructional Software Design Project (ISDP)

In the first instantiation of the Instructional Software Design Project, 4th grade students built LOGO programs to teach 3rd grade students about fractions (Harel & Papert, 1990). In an extension of that work, 5th grade students designed software for 4th graders, and then became consultants for the 4th graders as they designed software for 3rd grade students. In this second instantiation, the older students enjoyed taking on the role of consultants for their 4th grade peers. "It provided students with a different audience from the one they usually have. In regular school-like situations – by facing a teacher, who by definition seems to know everything – students might feel intimidated to announce their ideas or problems, discuss their theories and raise hypotheses (Kafai & Harel, 1991)." In other words, the students were able to approach the learning task from a more playful and novel perspective that allowed them to leverage social interaction with their peers to shape and refine their understanding.

One benefit of consultation for learning is that it provides the students an opportunity to step back from the creation process and think about it from another person's perspective and with another person's goals in mind. Kafai and Harel demonstrate that this greater "cognitive distance" from the learning process generates conflicts in the consultant's own knowledge and understanding. Through the process of explaining his ideas to the consultee, the consultant examines his knowledge more closely and is better able to recognize and address any "cognitive conflicts" that he encounters.

An important goal of the social system in AquaMOOSE is to provide a compelling audience that will motivate students to create interesting mathematical artworks. The ISDP project shows that consultation sessions are one way to get students engaged in the learning task by providing them with a novel audience. Students participating in the AquaMOOSE evaluations were encouraged to help each other informally at any time. During a formal critique session in the most recent after-school program we conducted, students were also encouraged to give each other critical feedback about works in progress. This experience gave students a chance to reflect on their own accomplishments and needs as well as those of their peers.

CHAPTER III

EARLY PROTOTYPES

Throughout its duration, the AquaMOOSE project has evolved in many different ways. The tool implementation has changed significantly. The curriculum surrounding the tool, the learning goals of the project, and the social context of the system have also changed. In this chapter, I present the initial phases of the AquaMOOSE evolutionary design story.

The AquaMOOSE design process began with a technology — 3D graphical avatar worlds. We began our research by exploring the basic affordances of that technology and looking for ways in which it might support learning. We did not begin by doing fieldwork with math teachers and math students. If we had, we would have learned a great deal about their needs in these areas and designed a very different sort of math learning software. Instead, we focused on expanding the learning possibilities rather than supporting existing learning.

Work on the AquaMOOSE project began in 1997. Since then, we have completed seven prototypes of our software and conducted many informal and formal user studies (see Section 1.5 above). Our first prototype, NetFlyer, was built using the OpenGL language. The second prototype was built with the Alice software developed at CMU by Randy Pausch and his colleagues (Conway et al., 2000). The last five implementations are MFC applications programmed in Visual C++ using a freeware rendering package called Genesis 3D. This chapter presents lessons learned from the first four prototypes of the AquaMOOSE system. The final three iterations are described in Chapters IV, V, and VI respectively.

3.1 NetFlyer (c. 1997)

Our first prototype, called "Net Flyer," was a simple two-person game similar to the American basketball game 'HORSE' (see Figure 3.1), created in OpenGL. Two players play at one terminal.

While one turns his or her back, the first player selects an equation. The second player views the graph of the equation (metaphorically, the path of a flying disk) and tries to guess the original equation. An unsuccessful guess earns a letter in the word "FLYER." The first player to complete the word "FLYER" loses. From this early prototype, we gained insight into the kinds of visualization supports we would need, such as the ability to switch cameras to make use of multiple views of the 3D world. In informal testing, users noted that the equations were often aesthetically pleasing. They also observed that it was important to keep equations simple if their opponent had any hope of guessing them. The game was more fun in a cooperative mode where you try to provide your partner with an appropriate challenge, rather than a competitive one where you try to stump him or her.

The mathematics involved in the NetFlyer prototype was simple. Participants could choose from a limited set of six trigonometric and polynomial equations, or the negative of those equations, to use as the path for their flying disk. One equation was chosen for each of the three Cartesian axes. The text output area provided instructions for playing the game as well as feedback about the state of the game. The top left area of the 3D space shows an overhead view of the flying disk, the top right area shows a side view, and the bottom area shows a perspective view as if from the eyes of the participant after throwing the disk. The two views at the top of the screen can be zoomed in or out, and the “person” in the bottom view can move to the sides or up and down to get a better perspective view of the 3D space.

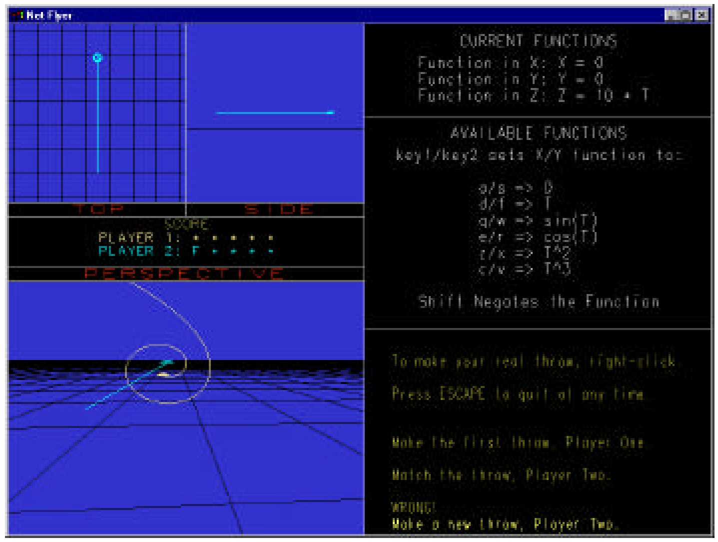


Figure 3.1: NetFlyer prototype game

3.1.1 Aesthetic Appeal of Trails

The NetFlyer prototype gave us a chance to explore the viability of using 3D parametric equations and trigonometric functions as an engaging medium for improving students' interest in mathematics. Our informal trials of the prototype gave us confidence that the system offered the type of motivating content we desired. The fundamental construct in the environment that made it appealing was the mathematical trails. Even combining very simple trigonometric equations in the three Cartesian axes produced aesthetically appealing, and often unexpected, mathematical trails. Though the unexpected nature of the resulting trails often made it difficult to win the actual game itself, the visual appeal of the trails as first-class objects in the environment indicated the potential of our system design for engaging students in constructive mathematical activities.

3.1.2 Multiple Cameras and Viewpoints

During our informal use of the NetFlyer prototype, we discovered that having more than a single view into the environment helped us understand the mathematical trails better. Other research on 3D environments has indicated similar results (Dede *et al.*, 1999). The fixed perspective views from the top and side of the 3D space provide valuable information about the components of the equations used to create the flying disk's path. In addition to simply having the extra views available, the real benefit of multiple views is apparent when the disk's motion is conveyed simultaneously in all views. Seeing an image such as Figure 4.1 is helpful, but seeing the path drawn simultaneously in all views allowed us to visualize how the component equations combined at various points during the path to create the interesting 3D trails that resulted.

3.1.3 Challenge of Understanding 3D Math

The mathematical trails created using the NetFlyer prototype encouraged us about the possibility of using this system to engage students in new types of mathematical activity. However, in our informal testing of the actual "HORSE"-like game, we found the simple 3D math difficult to understand even for graduate students in computer science. Math curricula at all levels of education tend not to focus on 3D parametric equations of any sort. The only exposure students might get to this type of math is in some higher-level physics courses where the motion of objects can be specified using parametric equations. This realization led us to focus more on tools and scaffolding (Collins et al., 1989; Guzdial, 1995) that might help students better understand the math they would use in our system.

3.1.4 Personal Relevance and an Open-ended Construction Kit

The goal of the NetFlyer prototype was to explore the possibility of using 3D math to engage students in new creative mathematical activities. The aesthetic appeal of the mathematical trails demonstrated the potential of the system for meeting that goal. One of the biggest drawbacks to the prototype, though, was the severely limited range of mathematics that could be employed. The prototype only included a small set of fixed math equations that could be used interchangeably in each of the three Cartesian axes. Our informal testing of the NetFlyer prototype clearly showed that the ability to create more varied trails that were personally meaningful was critical to the success of our system.

3.2 Alice Prototype (c. 1998)

The original NetFlyer prototype had a very primitive interface. Since the goals of the project included leveraging the aesthetic appeal of 3D graphics, we knew we needed to improve the look of the software. To move toward that goal, our next prototype was developed using Randy Pausch's "Alice" software (Conway et al., 2000). In that version, we created a 3D avatar world with the same flying disk game theme from NetFlyer (see Figure 3.2).

Compared to our first prototype, this new avatar world seemed much more fun, at least on the surface. The visual look and feel bear a resemblance to game-like environments, and the graphics are attractive. However, it was also much harder to understand the mathematics of motion in 3D. In our first OpenGL prototype, the user's position was fixed, making the orientation of the coordinate system consistent and clear. With the moving point of view of a first person system, the underlying math became harder to understand visually. This observation informed our addition of visualization supports like overlaid axes, grid tools, and multiple viewpoints in our next prototype.

The Alice software proved to be an excellent prototyping tool. However, during our exploration of the Alice prototype, we noted a limitation to our theme: the disk moves in three dimensions, but the user's avatar is stuck in a plane. We also recognized that in order to keep the game-like feel of a 3D world but make mathematical understanding easier again, we needed finer control of the user interface.

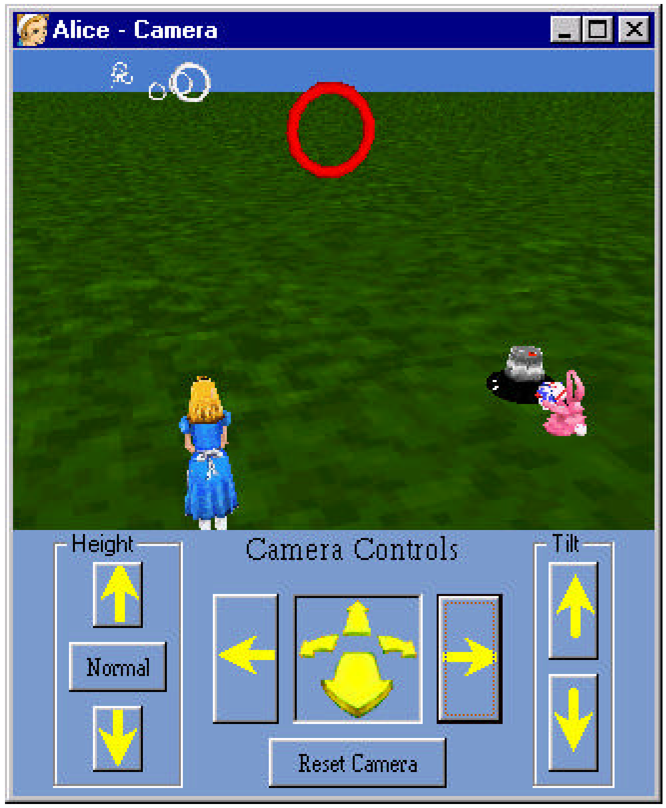


Figure 3.2: Alice prototype of NetFlyer

3.2.1 The Ring Game

In the Alice prototype, we introduced a modified version of the original flying disk game where the users' mathematical paths are represented in the 3D space by sets of rings. After a path is selected, the opposing player guesses the mathematical equations that will cause the flying disk to pass through all of the rings. The larger area of the rings allowed for some variation in the mathematical equations, giving players a chance to successfully complete the challenge without guessing the exact equations used to create the mathematical path. This game is called the Ring Game. The design of the ring game was influenced by Sharon Dugdale's "Green Globs" software (see Section 2.5.5). In her work, Dugdale showed that the game was motivating for students and encouraged them to explore math in novel ways (Dugdale, 1982). Our implementation of the Ring Game was also designed to provide motivation for students to explore novel 3D parametric equations, and to address the difficulty concerns we encountered during our use of the first prototype, NetFlyer (see Section 3.1.3).

3.2.2 Control of Software Code and User Interface

The Alice toolkit provided us with a starting point to create a 3D environment where students could visualize and maneuver around mathematical creations. However, the development tools were targeted more specifically at creating 3D animations rather than complex interactive 3D environments. We realized early in the development of the Alice prototype that the development tools would limit our ability to implement certain features. In addition, the research team developing the Alice tools had goals of their own that did not necessarily match the goals we had for the NetFlyer project. Working within the constraints of another research team's code base did not give us the flexibility to design interface components and game components that would improve our system. To more fully realize our goals of creating an interactive 3D math environment, we decided that we should develop our own code base rather than trying to adapt the Alice tools to our needs.

3.2.3 Visualization and Support Tools

The Alice prototype gave us a better idea of how a true 3D environment for exploring mathematics would operate. Through our use of this prototype, however, it became clear that understanding the positioning of the rings in 3D was still quite difficult, especially from a first-person perspective camera view. In the screenshot above (see Figure 3.2), the rings fade off into the background, leaving the user with little information about what math equations will replicate that path. We needed to add in scaffolding supports to help students grow to understand the 3D mathematics involved in the game. This realization prompted the implementation of various axis and unit visualization tools in future prototypes.

3.2.4 Limitations of the Flying Disk Theme

The greatest limitation of the Alice prototype resulted from the flying disk theme itself. Using this theme, the player is stuck walking around in a 2D plane while the disk is thrown in the 3D space using mathematics. Constructionist philosophy tells us that people learn particularly well through creating and sharing personally meaningful artifacts. After the development of the Alice prototype, we discussed ways in which the system could be modified to make the activity of the user more personally meaningful. The theme that emerged from those discussions was an underwater 3D environment where the user specified his or her avatar's movement in the 3D space, rather than moving an external object mathematically. This change in theme prompted a reconsideration of the system's name, since NetFlyer referred directly to the antiquated theme.

3.3 AquaMOOSE Multi-user Prototype (c. 1999)

To better make use of free movement in all three dimensions, we switched to an underwater theme—fish swim freely in three dimensions. Since this work is partly inspired by our prior research on end-user programmable textual worlds in the MOOSE Crossing project (Bruckman, 1998; Bruckman & Edwards, 1999), the new project was jokingly dubbed "AquaMOOSE 3D." While the name was proposed as a joke, it stuck. At this stage, we moved to a new development platform that gave us more control over the user interface: Microsoft Visual C++ and the freeware Genesis 3D rendering engine (Eclipse, 1998).

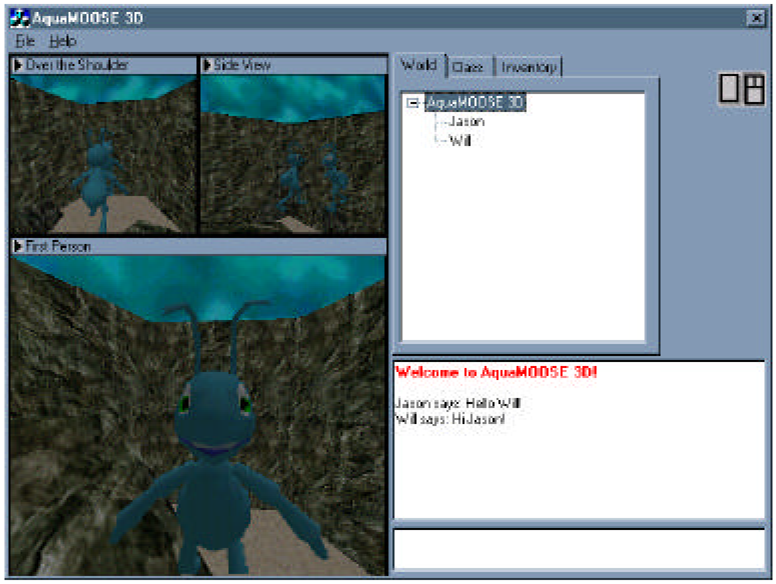


Figure 3.3: AquaMOOSE Multi-user Prototype (c. 1999)

This major switch in platforms necessitated a long engineering process that consumed many hours of the project team's time. Understanding Windows programming and MFC were critical to the project's development. Microsoft provided funding for two of our developers to participate in a Windows programming course offered by a third party corporate training group. We also spent a number of months experimenting with several 3D rendering packages, as well as attempting to write our own from scratch. This process eventually led to the realization that we did not have the resources to create a specialized renderer, nor did we have the funds to license commercial renderers such as the Quake engine. Instead, we chose to incorporate the reasonably flexible and adequately powerful freeware rendering engine, Genesis 3D. A similar round of experimentation with both commercial and experimental networking packages resulted in the opposite decision, however. We were unable to find a networking package that was clean enough to use and powerful enough to accomplish the tasks we had in mind. We began writing the first of many AquaMOOSE networking packages using standard C code.

After engineering these individual components, we were able to create a working multi-user prototype using a client/server model to provide communication and synchronization between many clients. Simple 3D worlds were created to demonstrate the possibilities of the new prototype, and placeholder artwork was used to represent the eventual fish avatars (see Figure 3.3 and Figure 3.4). During this phase of the project, several personnel changes along with technical limitations and scalability concerns resulted in a different overall direction for the AquaMOOSE system that focused on individual learners creating mathematical trails in private virtual spaces.

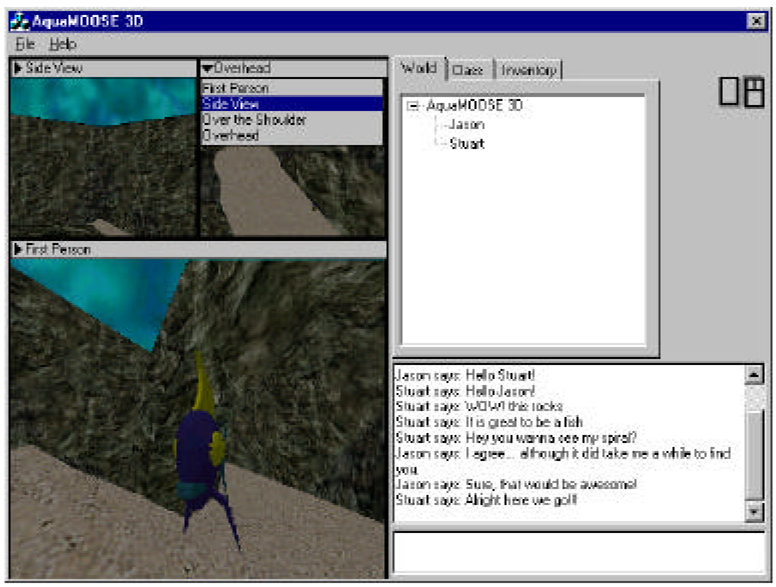


Figure 3.4: Fish avatars in the multi-user prototype

3.3.1 Scalability Concerns

During the multi-user prototype phase, we attempted to create an environment similar in structure to a massively multi-player online game. Many participants could be creating objects simultaneously in the same 3D virtual environment. This created numerous problems with scalability. Technical limitations (see Section 3.3.3) as well as pedagogical concerns led us to reconsider the multi-user environment design decision.

The goal of the system was to provide students with a way to creatively explore new mathematical constructs through building artifacts with trails. While having other people exploring in the same environment has obvious benefits for collaborating and sharing, the idea of "virtual clutter" began to outweigh those benefits. Students who are exploring in the AquaMOOSE environment often leave older trails around while creating new versions, comparing the results of both to see which is more appealing. With numerous people doing this in the same environment, the 3D space quickly started looking like an aquarium in dire need of a cleaning. We recognized that there was a trade-off between allowing students to fully explore the mathematics and having them participate in a shared collaborative space. In later versions, we attempted to reconcile this dilemma by providing single-user 3D spaces that could easily be populated with artifacts created by other users.

3.3.2 Feasibility of Fully End-user Programmable 3D Environment

The multi-user prototype of the AquaMOOSE system did not include a way for users to create mathematical artifacts. At this stage of the project, we were attempting to develop a scripting language similar to that used in the MOOSE Crossing project (Bruckman, 1998) that would allow students to fully explore math in a 3D virtual space. This scripting language, along with the programming interface for it, went through numerous design iterations. However, our discussions of the scripting language raised several concerns about the feasibility of a fully end-user programmable 3D environment.

Our focus was specifically on mathematics learning, but to allow users to program behaviors in a 3D space would require much more than just math. We needed to give them control of physical objects in the environment, provide them with a way to deform or morph objects as the result of a script or program, and give them a way to easily add new 3D objects to the environment. In the MOOSE Crossing environment, children can create a dog and write a description of the dog that includes its color, how its eyes look, and how it wags its tail whenever someone comes near. Then they can write a script for the dog that makes it bark whenever another object bumps it. Doing a similar task in a 3D environment would involve a modeling tool to create the visual appearance of the dog, animation tools to allow the dog to wag its tail and respond to actions, and a complicated scripting language to allow for realistic interaction between multiple objects in the space. While other systems have shown that none of those features are impossible to achieve, we began to realize that creating such an environment did not match our research agenda.

3.3.3 Technical Limitations

The rendering tools we used to develop the AquaMOOSE system had trouble keeping up with more than a handful of fish avatars in the environment simultaneously. Networking infrastructure was also difficult to design for handling actions from a large number of participants in a single environment. At the time this prototype was developed, popular MMORPG's such as EverQuest were just beginning to solve these problems. Without a full commercial development team or at least a few more doctoral students from relevant areas, we realized that we were not going to be able to implement a reliable infrastructure to support any type of scalable multi-user environment. These technical limitations combined with the pedagogical concerns discussed earlier (see Section 3.3.1) to lead us to a single-user system design that was much easier to support from a networking and rendering perspective.

3.3.4 Choosing Development Tools

The multi-user prototype was created immediately after the Alice prototype, where we found that using other researchers' software did not allow us the flexibility we needed. However, we continued to explore using commercial products to provide our system with more stability and robustness. We considered several networking packages that were designed to support the emerging genre of online 3D game environments. Many of the products had similar issues to our own networking code, and depending on external developers to fix bugs and address performance concerns harkened back to our attempted use of the Alice software. Likewise, we tried to explore other rendering options that would give us a higher visual quality than the Genesis3D freeware engine. Licensing fees for commercial rendering packages were significantly beyond our budget, and writing our own renderer from scratch proved a formidable task. The result of these engineering dilemmas was that we chose to use the Genesis3D renderer and to write our networking code from scratch.

3.4 AquaMOOSE Single-user Prototype (c. 2000)

Over the next year, we concentrated on developing a single-user environment focusing on mathematical trails as its primary artifacts. The method for controlling objects in the world was originally envisioned as a pseudo natural-language scripting language with a programming interface similar to that used in MOOSE Crossing (Bruckman, 1998). However, based on the lessons we learned during the multi-user prototype stage of the project, the scripting language was abandoned in favor of a simpler direct method of entering mathematical equations.

A simple template was created to scaffold (Collins et al., 1989; Guzdial, 1995) the process of entering mathematical moves. Each time a math move was executed, the avatar moved along the programmed function, leaving a trail behind. For example, swimming in a sine wave in x, a cosine in y, and a constant in z created a spiral. The trail provided the users with a visualization tool for instant feedback and a starting point for conversation (see Figure 3.5).

Despite the shift from a multi-user environment to a single-user environment, the system was still viewed as an online community where many users, each in their own personal space, would communicate via real-time chat. Visualization tools such as the absolute coordinate axes and relative axes helped users better understand the mathematical trails they created.

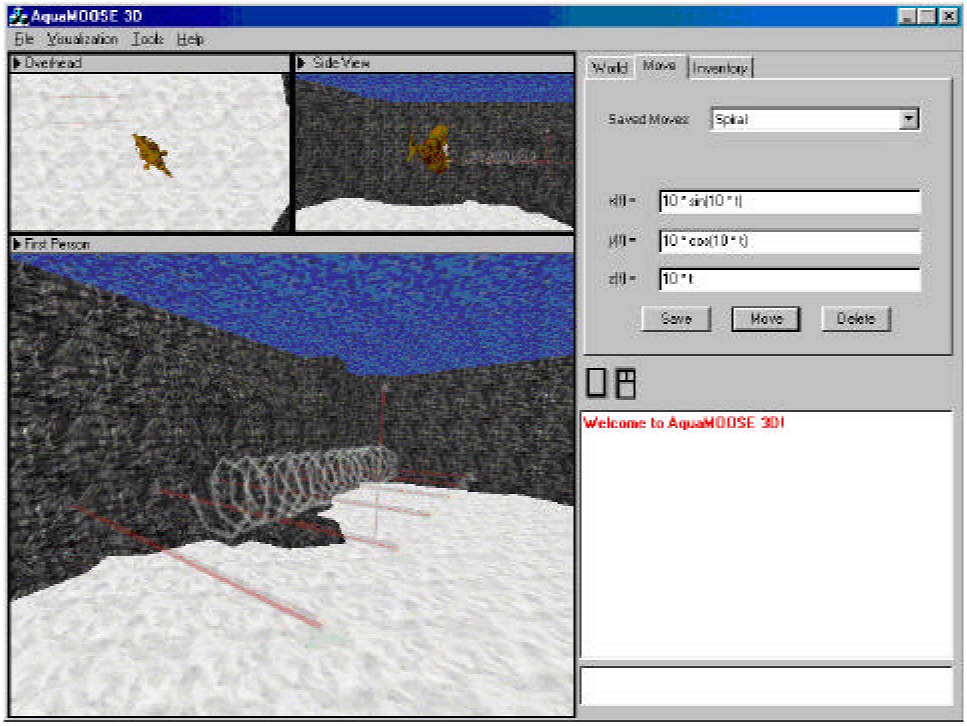


Figure 3.5: AquaMOOSE single-user prototype

3.4.1 Mathematical Trails as Primary Artifacts

The single-user prototype reintroduced the mathematical trails that had been missing from the system since the original NetFlyer stage. At this stage of the system evolution, we realized that the math trails were really the centerpiece of the whole socio-technical system. Both from a visual standpoint and a pedagogical standpoint, the trails are the most critical component in the environment. The trails allow students to reflect about the math they used in a real and meaningful way. They also allow students to create personally meaningful artifacts within the virtual environment that can then be shared with other people. Through this stage and into the first large-scale public release (see Chapter 4), we began focusing more on the trails as first-class objects in the world. Instead of having students create catfish or other pets that had mathematical behaviors, they could create visually appealing 3D mathematical trails that demonstrated the same types of personally meaningful characteristics.

3.4.2 Math Equation Interface

For the first 3 years of the system evolution, we envisioned a scripting language that would control the mathematical behaviors of objects in the 3D space. Given our realizations from this and the previous prototypes about the feasibility of such a system, we decided to focus the creation process specifically on mathematical trails. We created a simple interface that allowed users to enter a parametric equation for each of the three axes. This interface underwent numerous changes throughout the later stages of the system's evolution, but the single-user prototype phase demonstrated that such an interface was sufficient and understandable for creating visually appealing mathematical trails.

3.4.3 Polar Coordinate Space

The single-user prototype allowed users to create mathematical trails using the three axes of Cartesian coordinate space. Cartesian coordinates use the perpendicular axes x, y, and z to describe the position of points in a 3D space. This coordinate space is easy to understand and is the primary coordinate space taught in most high school math classes. However, due to the linear nature of Cartesian coordinate space, the math trails created using the single-user prototype of the AquaMOOSE system tended to be somewhat boring. The ability to include trigonometric functions in the equations dramatically increased the variety of trails possible, but there still seemed to be a limit to the system's ability to create truly personally meaningful artifacts based on mathematical trails.

In addition to increasing the variety of math trails, adding more coordinate space options seemed to be an obvious way to use the 3D space to help math students understand the differences between various coordinate systems. The next two stages of the system's evolution included an additional coordinate space for each new prototype. The GHP release included cylindrical polar coordinate space, and the BHS release also included spherical polar coordinate space. Polar coordinates allow users to create interesting curves with much simpler equations than would be required if using Cartesian coordinates and trigonometric functions.

3.4.4 Sharing Creations

The change from a multi-user environment to a single-user environment necessitated a new method for sharing users' creations with other people. This raised many design questions about exactly what participants should be able to share and how they should share it. Should users be able to load a complete world just as the other person left it? If so, how does that impact objects the user may already have created in the environment? Should objects that are loaded into someone else's environment be editable or only viewable? Ring games are designed as challenges for other players to complete. How should they be treated differently than math trails that are created simply for aesthetic purposes? How do users browse and load other people's creations?

In preparation for the first release of the software, we addressed these issues by implementing a "gallery" of artifacts that could be loaded into an environment (see section 1.4.2.3). The gallery is designed to allow users as much control as possible over how their creations are presented to other participants. Based on our constructionist pedagogy, we know that sharing creations with an audience is a critical component of the learning process. During the single-user prototype stage, we began shifting our design efforts to improve the social aspects of the system, such as sharing creations with other users and providing an appropriate context for participants to engage effectively with the system.

CHAPTER IV

AQUAMOOSE SUMMER CAMP RELEASE (2001)

Based on the lessons we learned in the previous stages of the project, as well as several rounds of informal user testing, we made a number of changes to the software before our first major deployment study at the Georgia Governor's Honors Program in the summer of 2001. The GHP version of the AquaMOOSE software is a single-user environment focusing on mathematical trails and ring games as primary artifacts.

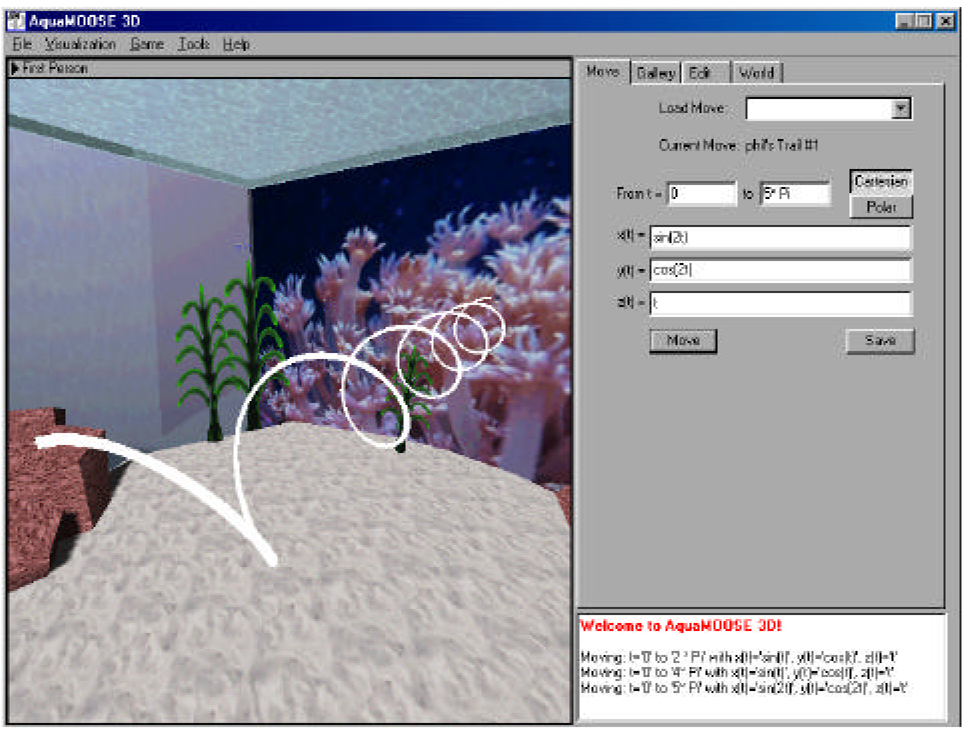


Figure 4.1: AquaMOOSE GHP Release

Users in the GHP release were able to communicate with each other via real-time chat, and were able to share their creations through an interface called the "gallery." The gallery contained a public folder and a private folder for each user. When a user created something, it was automatically stored in his or her private folder. Once the user felt comfortable with the artifact and wanted to share it with the rest of the participants, he or she could simply click and drag the object into his or her public folder. The gallery distinguished between simple math trails and ring games, allowing users to copy and edit math trails but only to play through other users' ring games. In this manner, participants were able to create ring games using a specific set of math equations and then challenge one of their friends to complete the ring game (see Figure 4.3).

The math interface had two new features that resulted from informal user testing and our experiences with the previous prototypes. The first feature is polar coordinates. The GHP release allowed students to create trails using either Cartesian coordinates or cylindrical polar coordinates. This release also gave the students more control over the range of the parameter used to draw the mathematical trails. When the points on the trail are computed, the "From" value is used as the trail's starting point and intermediate points are calculated using values of the parameter 't' up to the "To" value (see Figure 4.2).

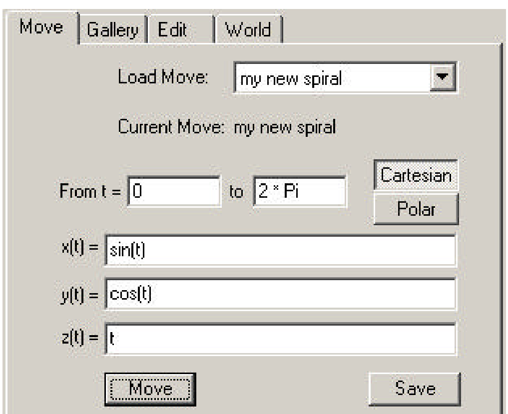


Figure 4.2: Math move interface

Although the GHP release was primarily a chance for us to get usability feedback about the software, it also allowed us to begin exploring more of the social aspects of the AquaMOOSE system. The GHP study was designed to be a "best-case" scenario for our research purposes. The students at GHP were already interested in mathematics and computers, and were attending a special summer program to explore new mathematical concepts. In keeping with the spirit of the GHP, we designed our study around the idea that these highly motivated students would use the software of their own accord during their free time.

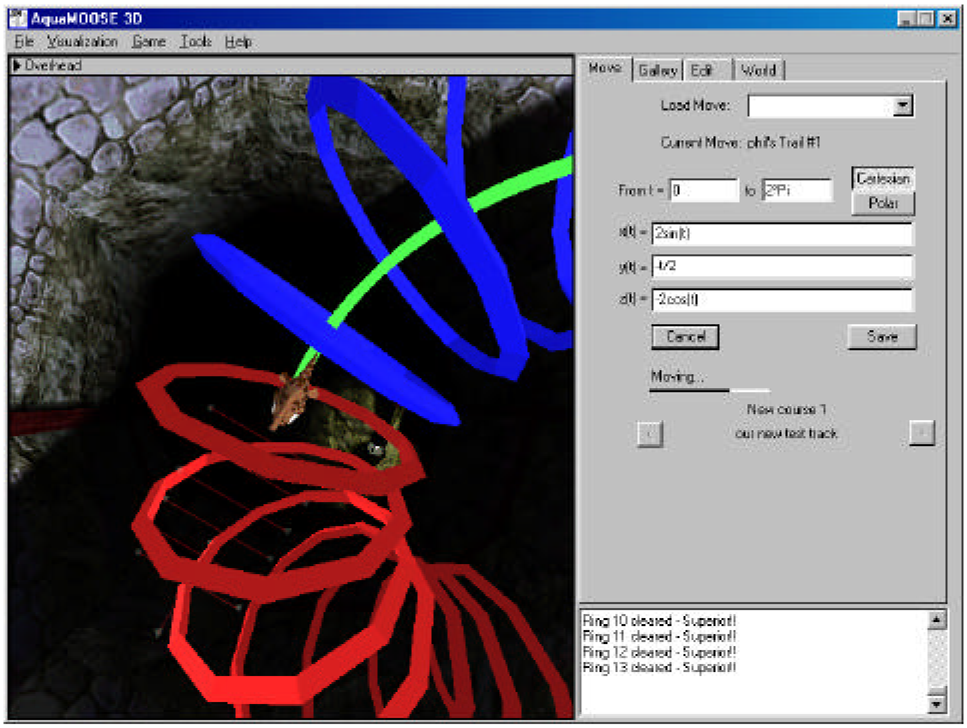


Figure 4.3: Ring Game during GHP release

4.1 Governor's Honors Program Study

The first large-scale deployment study of the AquaMOOSE system was conducted at the 2001 Georgia Governor's Honors Program. This study was designed to get general feedback about the usability of the software and the potential of the system for engaging students in a new type of math learning. Once the software tool was introduced, no other structure was provided. Students were able to use the software during their free time as much or as little as they desired. An extreme view of the constructionist philosophy would say that such structure allows students the freedom to choose personally meaningful projects entirely on their own using the tools provided to them.

This section begins with an overview of the study and a summary of the state of the AquaMOOSE software during this time period. Then results from the surveys and interviews are presented and discussed. More insights from the study about the usability of 3D environments are next, followed by a case study of one student's unique and informative experience with the AquaMOOSE system.

4.1.1 Study Overview

In summer 2001, we conducted a study at the Georgia Governor's Honors Program (GHP) in Valdosta, Georgia. Each year, rising juniors and seniors from Georgia high schools are nominated to attend a six-week summer camp to explore a particular academic area. One of the subject areas offered at GHP is mathematics. There were 105 students majoring in math at GHP that summer. Those students were the subjects for our study. We installed the AquaMOOSE software on 31 computers in the GHP labs that the students used for classes. The students also had access to these labs when classes were not being taught. One of the mandates for the GHP is to enrich students' learning experience beyond what they encounter in the standard curriculum. That aligns very well with our fundamental research goals, making the GHP an ideal setting for this trial.

The study began with a 45-minute demonstration of AquaMOOSE 3D. After that, the students were allowed to log into AquaMOOSE freely. After the introduction, they were not required to use AquaMOOSE at any time. We were more interested in collecting data about how the students used AquaMOOSE during their free time than during required time. There were many other projects and activities at GHP that the students could participate in during their free time. Playing with AquaMOOSE was only one option for the students. All of the data presented in this section was collected from students who voluntarily used AquaMOOSE throughout the summer.

Students had access to the software in a computer lab setting. Students were able to talk to one another and discuss their progress while using the computers, but generally used the software individually. We collected log files detailing the students' usage of AquaMOOSE over the next six weeks. We returned to GHP halfway through the summer and observed the labs during students' free time. Our final visit to GHP was at the end of the program, when we collected anonymous surveys from 103 students (2 had left the program during the summer) and conducted interviews with 10 students. The GHP lab administrators and instructors chose the 10 interview subjects who had shown the most interest in AquaMOOSE during the summer. Most of the students who were interviewed found the graphical nature of the program appealing, but wanted more features and more goals to the game. Many of them wanted the fish to be able to jump out of the water or be able to eat other fish. After the study, we did a more in-depth interview with one outstanding student.

4.1.2 Technology Summary

During the GHP study, the AquaMOOSE system focused on creating games using mathematics. Users were able to create mathematical trails, but they were encouraged to consider how they might use that capability to create games. The software provided one sample game called the Ring Game, where a set of rings could be placed in the environment based on a set of parametric equations. Once such a ring track was created, it could be added to a container object called a ring course. Users could challenge their friends to play through a ring course, in much the same way as someone might play through a golf course in real life. The player would see the rings laid out in the environment and then guess what equations would move the fish avatar through those rings. As the avatar successfully passed through a ring, the ring changed color and a message was sent to indicate how close the fish passed to the center of the ring (see Figure 4.4).

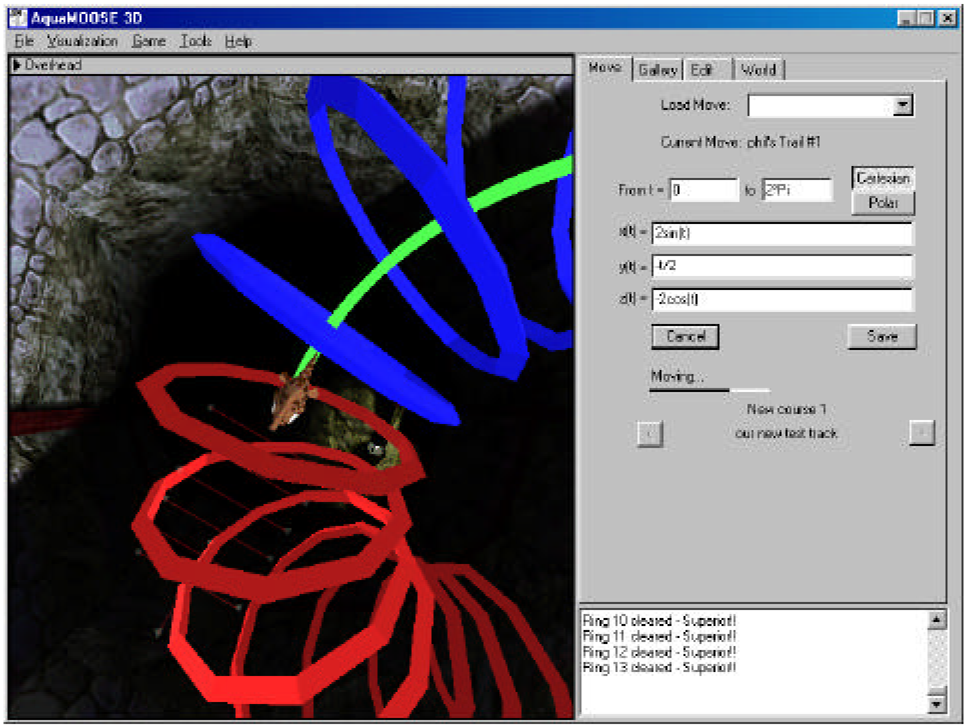


Figure 4.4: Ring Game during GHP release

The software allowed students to use either Cartesian or polar coordinate space to create their trails and ring games. Ring games and saved moves could be shared via a network component called the Gallery. The Gallery provided a public folder and a private folder for each user. When an item was created, it was stored in the private folder until the user decided it was complete and dragged it to the public folder. Once in the public folder, other users could see and use the object. Saved moves could be manipulated by other people, but ring games could only be played through without seeing or editing the actual equations (thus allowing users to challenge others to complete their ring courses).

4.1.3 Results and Discussion

There were 105 math majors at GHP who completed parental consent forms for our study. We asked the students to provide their real name and a pseudonym to be used in the software. Many of the students, however, did not provide their real name. In addition to the 105 math majors at GHP, students from other programs had access to the computer labs and our software. Since some of the math majors did not provide their correct real name when registering for an online account, they were indistinguishable from the students who had not signed consent forms. Due to that problem, we are only able to report on the data from those accounts that are verifiable as having provided parental consent for our study. Of the 105 math students, 63 created verifiable accounts. Of those 63, 37 students (59%) performed at least one mathematical movement. The total number of mathematical movements performed by all 63 students was 962. One student, Mark, was responsible for 340 of those moves. We discuss Mark's experience in greater detail below.

Table 4.1: Sample questions from the survey

• Were there things that you wanted to do in the environment that you couldn't do?
• What could we do to improve AquaMOOSE 3D?
• Would you be likely to play with AquaMOOSE 3D if it weren't for a school assignment?
• What were your favorite and least favorite aspects of AquaMOOSE 3D?

At the end of the six-week study, we distributed anonymous surveys to the students. The majority of the questions on the survey were open-ended discussion questions. See Table 4.1 for some examples of the questions we asked in the survey. Two reviewers analyzed the surveys. During that analysis, the reviewers noted whether each survey mentioned particular topics of interest. The six topics we chose to explore were negative aesthetics, positive aesthetics, game goals, violence, community, and competition. Some examples of comments for each of the categories are shown in Table 4.2. Our average inter-rater reliability was 84%.

Table 4.2: Sample comments from surveys

Topic	Sample Comment
Negative Aesthetics	"[I wanted to] swim in a larger environment with more space."
Positive Aesthetics	"The environment and the trails were some of the best parts."
Goals to the game	"I think I might play around with it for a little bit but not regularly because I don't feel like there's any goal to it or clear way to win."
Violence	"[I wanted to] eat the smaller fish."
Community	"I would play… longer if I could interact and share stuff with my friends."
Competition	"[I wanted to] race with others."

Out of the 103 students, the number who mentioned aesthetics in a negative manner (56) was almost identical to the number who mentioned positive aspects of the environment (55). Many students requested more structured goals in the environment (18), more violence (14), or more community involvement (12). A few of the students specifically requested that competition be a more integral part of the software (5). These results are shown in Table 4.3.

Table 4.3: Anonymous survey results

Topic	Occurrences (N=103)
Negative Aesthetics	56 (54%)
Positive Aesthetics	55 (53%)
Goals to the Game	18 (17%)
Violence	14 (14%)
Community	12 (12%)
Competition	5 (5%)

4.1.4 Usability of 3D

As we expected, the majority of the students mentioned that the 3D graphics in AquaMOOSE were appealing. They enjoyed editing their fish avatars, looking at the math trails they created, and exploring the various 3D worlds that were provided with the software. One of our basic premises for this project is leveraging the appeal of 3D games to improve students' motivation to learn mathematics.

While they liked the visual look of AquaMOOSE's graphical world, many students experienced problems navigating in it. Some of the problems involved the navigation controls, while others involved representational problems about the virtual world. The size of the environment that we should provide in AquaMOOSE is a difficult design problem. Overall, larger worlds are more popular with the students because they offer more opportunities for exploration. However, there is an important difference between providing interesting places for students to explore and providing large open places for them to explore mathematics. Some of the worlds we included during the GHP study contained interesting "hidden" features that the students could discover through exploration. However, none of the large open spaces we provided were big enough for many of the mathematical moves the students attempted.

One of the most prominent comments we received from the students was that they did not like colliding with walls (referred to as “bonking”) because their math moves did not fit in the world. Since the GHP study, we have constructed a few very large worlds to help alleviate some of those space concerns. Simply creating larger worlds does not solve the problem, though. In the larger worlds, moving an avatar from one side of the world to the other with our standard mouse and keyboard navigation controls takes quite some time. The key issue for this problem is the scale factor between the mathematics and the world geometry. One solution we have implemented is allowing the user to manipulate the passage of time, which controls the fish avatar’s movement. The user can increase the time constant and move quickly across large spaces.

Another important aspect that we learned from this study is that visualization of math trails is interesting to the students. The students had not been exposed to this type of mathematical visualization before, and described wanting more tools to help understand the graphical representations. Many students wanted more cameras to move around in the environment. They also wanted more control over what was shown in the cameras that we provided.

4.1.5 Mark’s Experience

Of the students at GHP, the most enthusiastic AquaMOOSE user was Mark. His experiences were by no means typical. We chose to examine his success story in detail to learn what went right. We have used those insights to guide our iterative design process.

Mark was 17 years old, and was a rising senior at a high school in a small Georgia town. Mark’s creations in AquaMOOSE drew the attention of his instructors and peers at GHP. His trails consisted of complex equations that he used to represent surface-like structures. Not only were they mathematically sophisticated, but also aesthetically pleasing (see Figures 4.5-4.7). We chose to study Mark's experience in detail to explore what factors aided his success. Why did he become more engaged than other students?

To understand Mark's experiences, we examined logs of his AquaMOOSE usage, interviewed him during GHP, and interviewed him again after GHP. Mark's favorite activities include playing guitar, writing poetry and short stories, and playing around with computer programs. Mark was nominated for GHP in both math and English. GHP offers a program in music as well, but Mark's high school did not nominate students for that major. He decided to attend GHP partly because he knew it would be good for his academic career, but also because he thought it would be an interesting social experience.

Since Mark attended GHP as a math major, one might guess that his favorite subject in school is mathematics. However, it turns out that is not actually the case. Mark says that his favorite subject changes very often, usually rotating between creative writing, music, and math. "I like all of them a lot, and it just depends on whatever strikes me… what I'm curious about that second," Mark says. Since AquaMOOSE is designed to take advantage of a synergistic combination of math and art, it is not surprising that the most enthusiastic user was equally interested in humanities and mathematics.

Mark thought he would like to become a computer programmer when he went on to college. However, he felt that his lack of experience with programming during high school would cause him to be behind other students at college. If that proved to be the case, he would consider an engineering career as an alternative. Regardless of which major he chose, he intended to get a minor in music, which he planned to use as a back-up career. He entertained thoughts of teaching music at some point during his life.

On arriving at GHP, Mark was surprised by the intelligence of his peers. Entering an environment where the majority of the students around you are the brightest at their respective high schools can be an intimidating experience.

There were many other activities going on at GHP that took away from the students' free time. As Mark pointed out in our interviews, GHP is a social experience as well as an academic one. Many of the students spent a great deal of time playing sports, attending dances, or just hanging out with their new friends. Mark balanced out those activities with his exploration of AquaMOOSE 3D. "There wasn't actually that much stuff that I wanted to go to that I missed," Mark says.

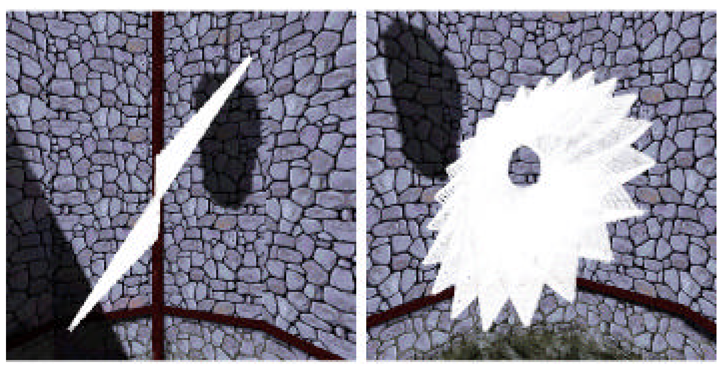


Figure 4.5: Two views of Mark's "slant vortex"

```
x(t) = .08 * (t + 10) * cos(40t)
y(t) = .08 * (t + 10) * sin(40t)
    z(t) = .08 * t * sin(40t)
```

Mark used AquaMOOSE mostly during his free time. After checking his email, he would play around with AquaMOOSE for a while. His typical sessions were anywhere from 15 minutes to an hour. There were other things on the computer that Mark could have used instead of AquaMOOSE, but none of them held his attention for very long. Even a text-based role-playing game that he had seen did not provide him with the entertainment that AquaMOOSE did. Mark usually enjoys playing video games, but is disappointed because many 3D games in particular contain too much violence and non-intuitive interfaces to the 3D environment. During the six-week period of GHP, Mark used AquaMOOSE for over 10 hours across 16 sessions. Even Mark's friends and teachers at GHP noticed his high level of involvement with the software. The teachers and students alike were impressed with Mark's creations in AquaMOOSE.

Mark's initial reaction to AquaMOOSE was frustration about the equation interface. The template for parametric equations in AquaMOOSE provides an area to enter the $x(t)$, $y(t)$, and $z(t)$ functions. Many of the students, like Mark, entered equations in the form $f(x)$, $f(y)$, and $f(z)$, using x, y, and z as the variables instead of t. In typical math classes, students most commonly see equations expressed in terms of x, y, and z. Most students have limited or no exposure to parametric equations expressed in terms of t. Since the software evaluated those other variables (x, y, and z) to zero, most of Mark's initial attempts at math moves produced no movement at all. The version of AquaMOOSE used at GHP was still in an early prototype stage, and did not provide the appropriate feedback to help correct such common mistakes. After a couple of days, though, Mark realized what the equations were expected to look like, and began experimenting with AquaMOOSE again. Mark spent most of his time in AquaMOOSE doing free exploration of complex math equations as opposed to playing with the ring game.

Mark's first exploration of AquaMOOSE involved playing around with the sample spiral move that was included with the software. The spiral consists of the equations:

```
x(t) = sin(t)
y(t) = cos(t)
   z(t) = t
```

These simple equations produce a visually appealing spiral in the 3D environment that was intended to spark the interest of students. After Mark played around with the spiral for a while, he moved on to more complex representations.

This second phase of his exploration resulted in what he describes as “a plane with a spiral coming out of it” (see Figure 4.5). Another one of Mark’s creations produced a trail that looks like a tunnel, except it has “barbed wire” sticking into the tunnel. Mark continued to experiment with various math functions. He added complexity to the equations in various ways. Some of his moves involved combining equations, like *tsin(t)* instead of just *sin(t)*. Some more examples of his work are shown in Figure 4.6 and Figure 4.7.

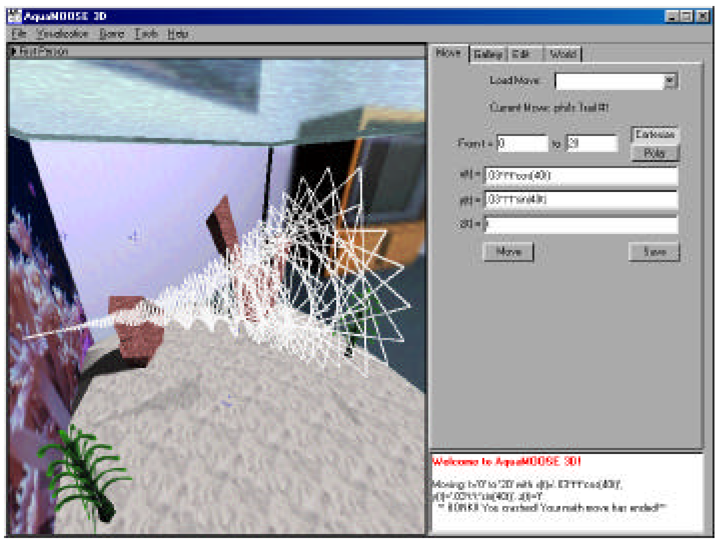


Figure 4.6: Mark’s complex “funnel” move.

```
x(t) = .03 * t * t * cos(40t)
y(t) = .03 * t * t * sin(40t)
z(t) = t
```

Eventually, a new goal emerged in Mark’s mind. He wanted to make a math move that formed a sphere in the 3D environment. He made several attempts at the sphere, but was unable to complete his goal. After the GHP program ended, Mark indicated that he was still thinking about how he could have made the sphere, and was disappointed that he didn’t have access to the software any more so that he could test his hypotheses.

In his high school math classes, Mark did not use computers very often. The main form of technology that he had been exposed to is a graphing calculator. The Texas Instruments graphing calculators are used in many math classes in the United States. Mark feels that AquaMOOSE offers a lot more than the graphing calculator. "Most of the time in math classes you don't have any way to actually represent 3D graphs. Sure, you can do 2D graphs; that's what the TI-83 is for… AquaMOOSE gave you the chance to do that stuff and had a user-friendly format where you could move around and leave a trail."

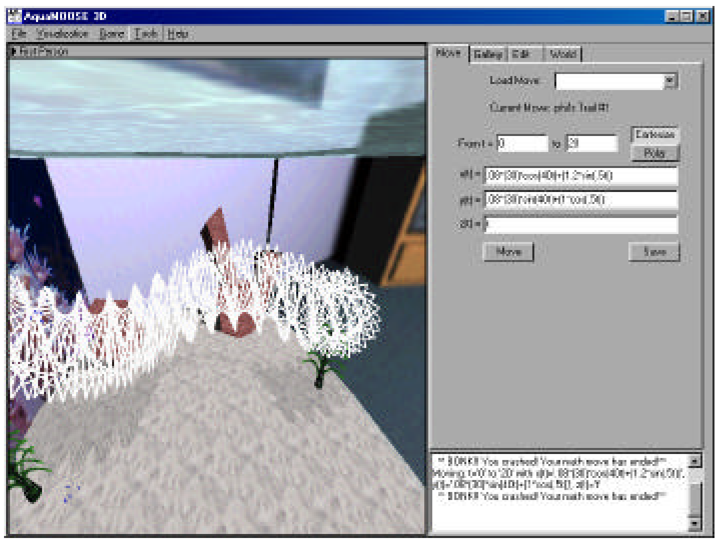


Figure 4.7: Mark's "spiral spiral" move.

$$x(t) = .08 * (30) * \cos(40t) + (1.2 * \sin(.5t))$$
$$y(t) = .08 * (30) * \sin(40t) + (1 * \cos(.5t))$$
$$z(t) = t$$

Mark speculates that teachers would appreciate using AquaMOOSE in the appropriate classes. He also thought that the teachers would probably spend their own free time exploring AquaMOOSE, since the 3D visualization is not supported well in other common tools.

A key question remains to be answered: what math did Mark learn? Based on the artifacts he created and our interviews with him, we know that he was successfully able to move from a goal to its execution. He wanted to create trails with particular shapes and aesthetics, and was able to do so through iterative experimentation. We know that he became increasingly fluent with combining basic mathematical elements to achieve his desired goal. We do not know to what extent that mathematical insight will transfer to other contexts.

4.2 Connections to Art

The GHP deployment study gave us a great deal of feedback on the usability and motivational appeal of the software. Out of all the lessons we learned in doing the GHP study, the most important realization we had was that the connection between math and art in the system was its core attribute. The AquaMOOSE project had always been about motivating students to learn new types of math through the use of visually appealing 3D graphics, but the GHP study highlighted the effectiveness of that synergy beyond what we expected.

Mark, whose experiences using the system during the GHP deployment are described in detail in section 4.1.5, thought of the math trails he created as works of art. He described his trails in terms of “barbed-wire” effects and “tunnels.” We realized that emphasizing the connections between math trails and artistic concepts would further motivate students to explore 3D mathematics in entirely new and unexpected ways. In future stages of the project, features were added to the software to allow students to present their artifacts in more specific ways. These new art/math synergy features allowed participants to color trails, animate trails, control the smoothness of trails, create sequences of trails, and combine multiple trails together to create coherent works of mathematical art.

4.3 Free-time Use

The GHP study showed that free-time use, even among students who were highly motivated to learn about math, was not a viable social context for our system. Out of the 105 students who were introduced to the software, only a handful used it more than once and only a couple really got involved with it enough to create interesting mathematical artifacts. The students needed more structure around the software in order to get anything significant from it. While the main goal of the GHP study was to get usability feedback on the software, we had also hoped that students would become highly engaged and create an enormous quantity of interesting mathematical objects. The lack of engagement from most students in the GHP study showed us that we needed to focus more carefully on the social aspects of our system to provide appropriate motivation and structure to help students become engaged. In the next two studies, we added more structure and support to the social context in order to increase students' likelihood of having a positive experience with the system.

4.4 Deployment Issues

This first deployment study introduced us to the difficulties of using networked technology in remote locations. The GHP was held on a college campus 200 miles away from our research lab. Since one of the main components of the software was the ability to share artifacts with other people, having network connections to a server was critical. On several occasions during the study, the development team was on location at the GHP site conducting surveys and interviews or observing students using the software. Server crashes during this time period were problematic and required coordination with other researchers back at the server site to help maintain the server. In future studies, we concentrated on locations that were more immediately available to help alleviate some of these problems.

4.5 Difficulty of the Ring Game

The ring game was provided to give participants a way to challenge each other in a similar fashion to the original NetFlyer prototype. In the GHP release, however, we found that the ring game was less effective than we had hoped. Students found it extremely difficult to complete another student's ring game. It turns out that it is much easier to create a ring course that looks challenging and is impossible to solve than it is to create one that is both challenging and fun to solve. The problem of creating a ring game with an appropriate level of challenge is similar to developing a curriculum unit that teaches certain concepts in school. Without more specific training and support, expecting the high school students in our target audience to create such ring games would be quite ambitious. Work such as the ISDP project (Harel & Papert, 1990; Kafai & Harel, 1991) has shown that students can benefit from designing and sharing software to teach other students, but creating that type of project would be an entirely separate research endeavor outside the scope of the AquaMOOSE system.

4.6 Participants' Initial Characteristics

The performance of students during the GHP study also indicated that our "ideal" conditions did not have as much impact as we anticipated. Many of the students, who were all chosen to participate in the GHP based on high achievement in mathematics, did not become engaged with the AquaMOOSE software. This led us to consider other characteristics that might influence students' experiences with the system. Perhaps only students who already had high visual ability or spatial reasoning ability would be interested in using our software. We decided to address these questions directly during the next deployment study by administering standardized tests of visual and spatial ability to see if those characteristics predicted adoption and engagement with the AquaMOOSE system.

CHAPTER V

AQUAMOOSE CLASSROOM STUDY (2002)

During the six months between the GHP release and the Brooks High School (BHS) release, our focus was primarily on developing curriculum and structure for the social context surrounding the AquaMOOSE software. The results from the GHP study indicated that free-time use was not as productive as we hoped, so in the BHS study we designed a curriculum to accompany the software that focused on particular learning goals.

The software was refined based on the feedback we received during the GHP study. Spherical polar coordinates were added, allowing students to create even more visually complex mathematical trails. The visualization tools and the interface for ring games were modified to make them easier to understand and use. Synergy between art and math were reinforced through better graphical presentation of the math trails and other artifacts. The entire rendering system was reconstructed to allow more flexibility in the appearance characteristics of math trails. The result was much smoother trails that could be colored and animated using various parameters.

We began designing our curriculum based on the standard curriculum unit used at BHS to teach polar coordinate space. Given the addition of spherical polar coordinates and the existing capability of the software to easily differentiate Cartesian and cylindrical polar coordinates, we felt that the AquaMOOSE software would enhance this particular curriculum unit. The curriculum we designed was for a one-week unit where three days were spent in the computer lab using the AquaMOOSE software. We administered visual and spatial ability tests as well as math attitudinal inventories to better understand how students' characteristics influenced their adoption and use of the system. We also spent several days working with the teacher to make sure she understood the software and its connection to the curriculum unit.

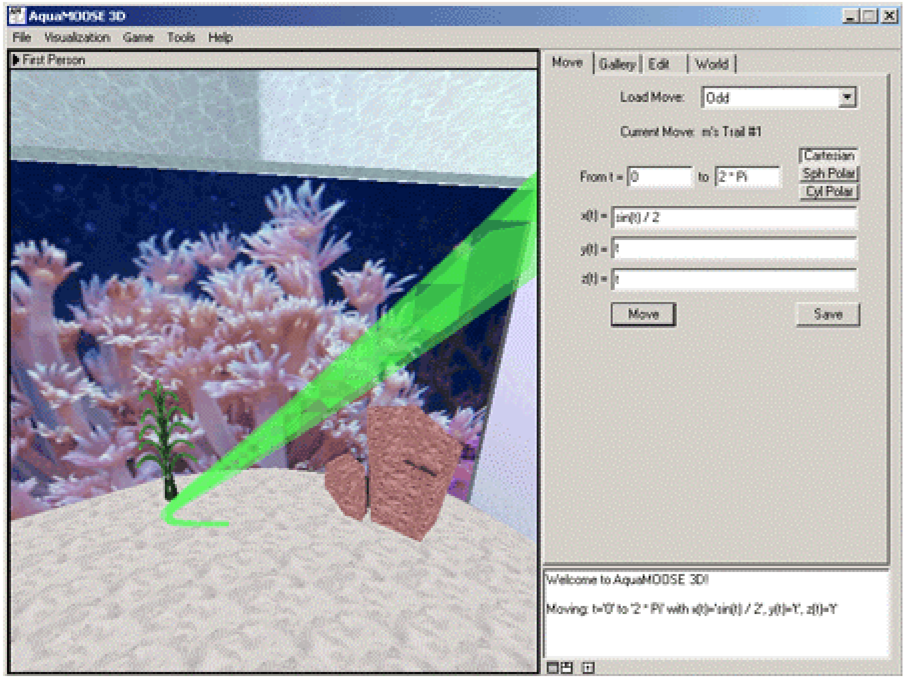


Figure 5.1: Math move during the BHS release

5.1 Brooks High School Comparison Class Study

The second large-scale evaluation of the AquaMOOSE system was in a local high school that we call Brooks High School (BHS). In this study, we designed a curriculum unit around the AquaMOOSE software to teach students about polar coordinate space. This unit was integrated into a pre-calculus class at BHS and the results were compared to another section of the same class that used the standard curriculum and tools. The goal of this study was to explore the capability of the AquaMOOSE system for meeting specific curricular objectives.

This section begins with an overview of the study and the software. The method of the study is then described in more detail. The results are presented and then a discussion of the implications of those results concludes the section.

5.1.1 Study Overview

BHS is a suburban public high school in central Georgia. The students at BHS are typically less advantaged and a large percentage of them receive free or reduced lunch. The teachers' expectations of the students and the students' expectations of themselves tend to be low. For example, the probable valedictorian of 2002's senior class planned to go to a local community college. When asked why she would not consider a four-year college, she expressed doubt about her qualifications.

The subjects for our study came from two pre-calculus classes at BHS. The two classes were roughly the same size (N = 30 and N = 34), and met in the same classroom and computer laboratory settings for the duration of the study. The same teacher taught both of the classes.

The teacher in our study, Kimberly, had been at BHS for 17 years. She had seen the school demographics transition from predominantly Caucasian to predominantly African American and had dealt with the racial tension that ensued. In several instances, her safety had been threatened on school grounds. In fact, when asked what the most challenging aspect of working at BHS was, she stated "the hallway." While she felt safe within her classroom, she had been called names, yelled at, and even choked by a student when walking around other parts of the school.

In late January of 2002, both of Kimberly's pre-calculus classes began studying polar coordinate space. This unit was taken from the county's Curriculum Guide for Advanced Algebra and Trigonometry. The comparison class for our study used the standard curriculum guide and tools while learning about polar coordinate space. The second class used the AquaMOOSE curriculum and the AquaMOOSE software in addition to the standard tools.

The Curriculum Guide states that the unit on polar coordinate space should last roughly one and a half weeks. The standard method for teaching polar coordinate space is by following Chapter 9, titled "Polar Coordinates; Vectors", in their textbook. Normal tools for the comparison class consisted of pencil and paper materials as well as hand-held graphing calculators (TI-83, TI-85, etc.). No extra software or technology was used in the comparison class.

Miller et al. note, "Learning outcomes achieved through microworld interaction depend largely on the surrounding instructional activities that structure the way students use and interact with microworlds (Miller *et al.*, 1999)." We developed the AquaMOOSE curriculum based on the standard curriculum found in the Curriculum Guide to help provide that structure. In addition to the standard topics, however, the AquaMOOSE curriculum included a review of trigonometric concepts, an introduction to parametric equations, an explanation of 3-dimensional functions, activities involving both cylindrical and spherical polar coordinate space, and a less structured lesson that focused mainly on the Ring Game portion of the AquaMOOSE software. The teacher covered parametric equations from the textbook in the comparison class to accommodate the requirements of the AquaMOOSE software.

The AquaMOOSE software was used to demonstrate various concepts during the week and a half unit on polar coordinate space. The software was tightly integrated with the AquaMOOSE curriculum. The software was available in the BHS computer lab for the duration of the study. All data from the students' use of AquaMOOSE was logged and stored on a server at Georgia Tech.

5.1.2 Technology Summary

The BHS study took place approximately six months after the GHP study. The software received some usability updates based on the feedback from the students at the GHP, but most of the components remained the same. Emphasis was shifted, however, from the ring game to creating trails in polar coordinate space. The math move interface was modified to allow the use of three coordinate spaces instead of two. The new interface provided separate options for cylindrical polar coordinate space and spherical polar coordinate space. This distinction was integral to the curriculum unit designed to accompany the software during the BHS study. The extension of 2D polar coordinates that the students learned from their textbooks to 3D cylindrical polar coordinate space was much simpler to understand than the extension of 2D polar to 3D spherical polar.

Students in the BHS study were still able to create ring games and to share all of their creations via the Gallery (see Section 1.4.2.3), but their primary goal was to explore mathematical trails and the differences between Cartesian and polar coordinates. The representation of those trails was refined for the BHS study to make them more visually appealing. Visualization tools were also improved to make them easier to understand and use.

5.1.3 Method

We began the BHS study by testing the students' visual ability and attitudes towards mathematics. We used three tests (CS-2, S-2, and VZ-2) from the Kit of Factor Referenced Cognitive Tests (Eckstrom *et al.*, 1976), available through ETS, to measure the students' visual ability. For our attitude survey, we used the Fennema-Sherman Math Attitude Scales (Fennema, 1976).

The length of the study was 8 school days. Table 5.1 below describes the activities of the comparison and experimental classes throughout the study. The first day was devoted to administering the pre-tests of visual ability and math attitudes. The comparison class met all 8 days in their normal classroom. They also took the visual ability and attitudes tests on the first day of the study. On the eighth day, the teacher handed back the content tests and went over the students' grades with them. We also gave the students a short questionnaire and a post-survey of their math attitudes. After completion of the unit, we conducted interviews with 3 students from the comparison class, 8 students from the experimental class, and the teacher. Three months later, at the end of the school year, we provided an open-ended survey about the content material and the math class in general.

Table 5.1: Study activities for comparison and experimental class

Day	Comparison Class Activity	Experimental Class Activity
1	Pre-tests	Pre-tests
2	Classroom work	Computer lab session
3	Classroom work	Classroom work
4	Classroom work	Classroom work
5	Classroom work	Computer lab session
6	Classroom work	Computer lab session
7	Content test	Content test
8	Review of content test; post-tests	Review of content test; post-tests

Our curriculum called for the students in the experimental class to have two days of preparatory work in the classroom, followed by three sessions with our software in the computer lab. However, due to scheduling conflicts, we were only able to get two consecutive days in the lab on the fifth and sixth days of the study. The only other day that the computer lab was available was the second day of the study, before the students had any exposure to the content material. That session was used to acquaint the students with the AquaMOOSE software. The third and fourth days were spent learning some of the content material in the classroom. The fifth and sixth days were spent in the computer laboratory. The content test was given on the seventh day.

The content test consisted of three sections. The first section covered material about the basics of polar coordinate space. The second section dealt with graphing polar equations. The third section was on parametric equations and 3D graphs of polar equations. The first two sections would have been covered regardless of our study. However, AquaMOOSE required the introduction of parametric equations in addition to polar coordinate space. The teacher covered parametric equations from the textbook in the comparison class, while the experimental class learned about parametric equations mainly through the use of the AquaMOOSE software.

Our hypotheses for this study dealt with a range of factors that might have affected the usefulness of AquaMOOSE in the classroom, including students' visual ability, math attitudes, and prior experience with video games. The following is a complete description of our hypotheses.

1. Students with higher visual ability will be more likely to benefit from using the AquaMOOSE software.
2. Students' attitudes toward math and math learning will be more likely to improve in the experimental class than in the comparison class.
3. Students in the experimental class will report a more positive experience learning these topics.
4. Students in the experimental class will exhibit more motivation in post-interviews about these topics.
5. Students in the experimental class will be more likely to remember this particular unit in the end-year survey.
6. The experimental class will show an improvement in their assessment of their teacher's support for their learning.
7. There will be no changes in the teacher attitude assessment for the comparison class.
8. Students with prior video game interest and experience will benefit more from AquaMOOSE both in math achievement and attitudes.
9. Students in the experimental class who score lowest on the spatial tests may show worse math attitudes in the post-test.
10. We have no prediction whether the experimental class will perform the same, better, or worse than the comparison class with respect to polar coordinates. Benefits of the software may be offset by wasted time going to and from the computer lab, and reduced teacher control of the learning situation in the computer lab.
11. The experimental class will perform better than the comparison class on parametric equations and 3D.

5.1.4 Results

We used the students' grades from the first semester of the pre-calculus class as a measure of prior mathematical achievement. The experimental class had slightly higher grades than the comparison class, but the difference was not statistically significant.

The results from the visual ability tests did not indicate benefits from the AquaMOOSE intervention on content test scores or math attitudes. There were no significant changes in students' attitudes about math during the study. The AquaMOOSE intervention had no impact on the students' performance on the content test or on their attitudes about mathematics. Students from the comparison class scored slightly better on average than students from the experimental class on each of the three sections of the content test. However, none of the differences were statistically significant. The students who indicated prior experience with video games had higher average scores on the content test, but the difference was not significant. The AquaMOOSE intervention did not increase the advantage of having prior video game experience (the students with video game experience in the comparison class did better than the students with video game experience in the experimental class). In short, all but two (#7 and #10) of the hypotheses listed above were not supported.

While the students showed some understanding of the subject material on the content test, our retention survey at the end of the school year indicated that very few of the students remembered anything about the unit on polar coordinates. This lack of retention was true of the students in the experimental class as well as the students in the comparison class. In response to a question on the retention survey about polar coordinate space, one student in the experimental class commented, "After the test I will forget, because it's not interesting to me."

Four of the eight students interviewed from the experimental class did not find the use of the AquaMOOSE software helpful in learning the content material. When asked if she enjoyed using the software, one student said, "I mean, I really didn't understand it overall. It was ok. But like just to do, I wouldn't do it. Not to just have fun. I didn't think it was fun. If anything, it confused me even more." Some of the students did see benefit from using the software, but noted issues about less time on task and confusion in the computer lab.

Student responses in the survey at the end of the year were similar. Some students had a positive impression of the software. One student said that while he did not enjoy AquaMOOSE as a game, he liked being able to visualize the mathematics in a better way. Many of the students expressed negative comments about the AquaMOOSE intervention. In response to a question about his or her least favorite part of math class, another student responded, "AquaMOOSE was aweful[sic]. I didn't learn a thing, my mind just got confused and unoriented[sic]."

5.1.5 Discussion

Before the study began, the teacher announced to her classes that one section was going to be using the AquaMOOSE software in the computer lab, and one was going to stay in the classroom. Of course, the students in the comparison class wanted to be the ones to use the software instead. They argued that they were "good at video games" too and should get a chance to use AquaMOOSE. Those students had high expectations of the software, and thought it was unfair that they were not allowed to use it until the study was completed.

Despite this initial motivation to use AquaMOOSE, many students in the experimental class were disappointed with the software. After the study, students in the experimental class commented on the lack of action in AquaMOOSE and the imperfect models and environments that we used. One student, in response to a question about polar coordinates, said, "I don't remember anything but the ugly little fish." By telling the students beforehand that they were going to be using software that was game-like in nature, we set the AquaMOOSE software up to compete against commercial quality software. As can be seen by the intense competition present in the commercial video game market, the students' high expectations are difficult to meet. For example, to create the massively multiplayer online role-playing game Asheron's Call, Turbine Entertainment had a staff of over 30 people working for 4 years (Ragaini, 2000). A research prototype made by a few graduate and undergraduate students and one faculty member clearly could not compete.

AquaMOOSE was designed to allow free exploration of 3D mathematics using primarily parametric equations and trigonometric functions. The math content of the AquaMOOSE software is very different from what is typical in high school math classes. 3D mathematics of any kind is rarely present in high school curriculum guides. The math in AquaMOOSE is not only different from anything the students had seen before, but is more difficult and is not on any of the standardized tests the students are required to take. Navigation in the 3D environment also creates confusion. Despite the use of a navigation scheme commonly used in popular games, many students had trouble controlling their avatar's movement in the 3D setting.

Like many typical school computer labs, the lab at BHS does not readily support a classroom atmosphere. Several factors, such as broken computers, insufficient space, not enough chairs, scheduling conflicts, and the arrangement of computers into rows facing different directions, contributed to making the computer lab an unproductive setting. Several new research initiatives incorporate the use of wireless handheld devices to support learning in the classroom as an alternative to computer labs (Roschelle & Pea, 2002). In reference to the problems associated with computer labs, Hickey et al. state, "that providing computer access *in the classroom* enhances the teacher's ability to use the technology-supported curriculum to support meaningful learning (Hickey *et al.,* 1999)." Based on those findings, avoiding the computer lab and providing technology within the more accepted learning atmosphere of the classroom would probably increase the impact of the AquaMOOSE intervention. In addition to problems with the computer lab, there were several problems in the classroom itself. During our study, there were several times when students were called out of class to participate in required testing or other school functions. Some students were disruptive during timed tests and surveys, distracting any nearby students. The classroom was generally a hectic and often unpredictable environment.

5.2 Curriculum Design

The curriculum we designed for the BHS study supplemented standard curriculum materials on polar coordinate space with use of the AquaMOOSE system. The AquaMOOSE software was integrated into the curriculum in an effort to provide students with an easy way to compare various coordinate spaces while giving the students opportunities to actually use polar coordinates in a more concrete and engaging way than by doing textbook exercises. The major difficulty in integrating the AquaMOOSE system with the existing curriculum was the conflict between standard curricular goals, which focus on learning specific concepts and demonstrating mastery of those concepts on a written exam, and the goals of the AquaMOOSE project, which are to learn through constructing personally meaningful mathematical artifacts and sharing them with other people.

As discussed earlier, one approach to doing educational technology research is to look at the current needs in the classroom and design an intervention to meet those needs. A second more radical approach is to look at the affordances of new technology to find ways that it makes new content appropriable. In the BHS study, we tried to use both approaches simultaneously. We began with a radically motivated design idea. However, in our curriculum design, we tried to link our intervention to the existing curriculum, and squeezed it into a few 54-minute class periods. While our software suggests an approach to learning in which different students might learn different math content through exploration, we decided instead that we wanted to try to guarantee that all students learn a certain core of math concepts. In the final version, our actual intervention looked a whole lot like the students' regular math classes; software that was originally intended to be a catalyst for constructivist learning ended up being used in a fairly traditional way. Therefore it isn't surprising that the learning results were nearly identical for the comparison and experimental classes. So are these uninspiring results a failure of overly radical software design, overly traditional curriculum design, or the uneasy marriage between the two? Our answer is an unequivocal “all of the above.”

5.3 Teacher Training

Despite our efforts to ensure that the BHS teacher was comfortable with the AquaMOOSE software, it became clear during the sessions that she did not have a sufficient command of the tool. Researchers observing the classroom sessions noted that the teacher often had trouble performing the examples with the software, and was not able to explain or help students who ran into difficulties using the software during the lab sessions. These difficulties were due to both bugs in the software and insufficient teacher training. The teacher in the BHS study was enthusiastic about participating in our research and devoted a significant amount of time and effort to the project. However, other responsibilities both at school and from extra-curricular activities made it difficult for her to really explore the capabilities of the software and become an expert user. This provided us with another important lesson about implementing educational technology research in real classrooms. Even the most dedicated and supportive teachers still need significant amounts of time, often more than they have available, to understand new technologies well enough to use them effectively in a teaching situation.

5.4 Expectation Management

Another problem that arose during the BHS study was the way the students’ expectations were managed. Before the study, the researchers and the teacher both presented the AquaMOOSE system as being similar to a video game, except for education instead of entertainment. The AquaMOOSE project has always aimed to leverage the visual appeal of 3D graphical online environments to help motivate students to learn about mathematics. Describing the system in that manner made sense in the context of research publications and presentations. However, as we saw in the BHS study, presenting the system as a game-like environment to the students set extremely high expectations for the quality of the software. The AquaMOOSE software is a remarkably stable and robust system compared to many research platforms, but without a team of professional graphic designers and programmers, it cannot compete with commercial video games like EverQuest or Quake. The expectation failure was clearly evident in the comments of students throughout the BHS study. Before the study began, students in the control class argued with the teacher that they should be the ones to use the software because they were "good at video games." But after the study, students in the experimental class commented on the lack of action in AquaMOOSE and the imperfect models and environments that we used. One student, in response to a question about polar coordinates, said, "I don't remember anything but the ugly little fish." Other factors certainly contributed to the students' eventual reaction, but carefully managing their expectations throughout the BHS study would have increased the likelihood of students having more positive experiences with the AquaMOOSE system.

5.5 Classroom Constraints

As any educational researcher who has studied real classrooms can attest to, there are many constraints in the classroom that can adversely affect the results of any intervention. Most school class sessions are short, and the amount of time spent on any particular topic is small. The county's curriculum guide described the curriculum unit on polar coordinates used in the BHS study as 7 one-hour classroom sessions. Implementing an augmented curriculum where students are introduced to a new piece of software and then use that software to achieve some learning goals with only 7 hours of time-on-task is unrealistic. At the end of the three computer sessions, the students in the BHS study were just beginning to understand what the software was capable of doing. They had no time left to explore the mathematical content in any meaningful fashion.

Another problem with classroom research is the variety of students who are present in class. Especially in average middle-class schools such as BHS, finding a classroom of students who are all motivated to learn the content material is unlikely. In the BHS study, we witnessed several instances where students would not only be avoiding participation, but would also be distracting other students and keeping them from participating as well. Despite the appeal of new technology and a novel experience (researchers are not common at BHS), many students were unmotivated to participate and learn from the software and materials we provided.

These constraints of real classrooms, as well as others, led us to again reconsider the social context surrounding the AquaMOOSE software. In our first deployment study at the GHP, we gave students the option to use the system in their free time with very little structure. In the BHS study, we provided much more structure and challenged the students to use the AquaMOOSE system to learn specific mathematical concepts. Neither of these approaches was successful in engaging and motivating students to learn. In the final study we conducted, we used these lessons to create a hybrid social context that provided students with a moderate amount of structure as well as creative freedom to explore the math content in personally meaningful ways.

CHAPTER VI

AQUAMOOSE AFTER-SCHOOL PROGRAM (2004)

The final version of the AquaMOOSE socio-technical system combined the lessons we learned in all of the previous stages of the project and focused on promoting connections between math and art. New software features were implemented to give users more control over the aesthetic characteristics of their creations. The social context surrounding the system was developed as a compromise between the free-time use of the GHP study and the curriculum-based implementation of the BHS study.

For this final study, we developed three major features that provided the students with more possibilities for creating and customizing their mathematical artifacts. Trail animation properties, trail sequences, and scenes allowed greater flexibility and diversity in the types of objects that could be created using the AquaMOOSE software.

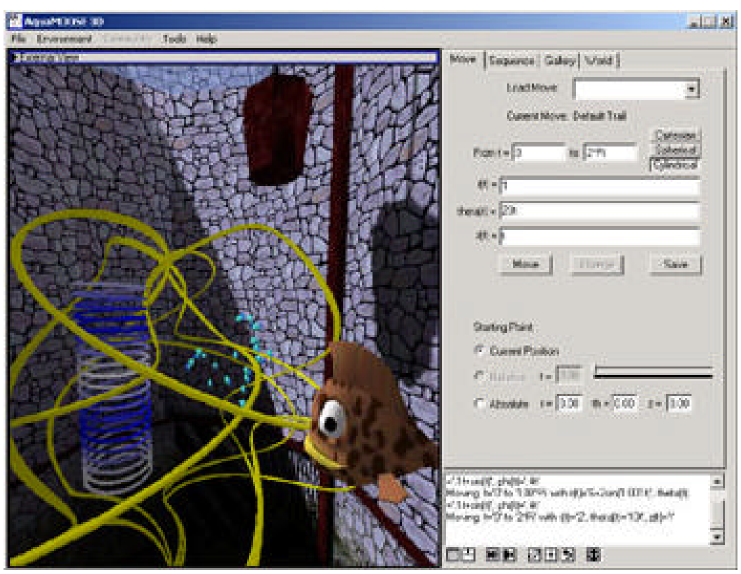


Figure 6.1: Customized trail properties

Trails could be drawn using a solid color or a blend of two different colors. When trails used two colors, the blend could be animated by either pulsing between the two colors or by shifting the colors down the trail in a sine wave pattern. The rate at which this animation occurred could also be controlled. In addition to colors and animation, the width of the trail could be changed to create thick or thin trails. Users could also change the number of segments calculated for a particular trail, which affected how smooth the trail appeared. Although increasing the number of segments also increased the amount of necessary computation, it allowed the students to control the appearance of trails in interesting ways. Computational artifacts could be used to create effects like "barbed wire" or moiré patterns.

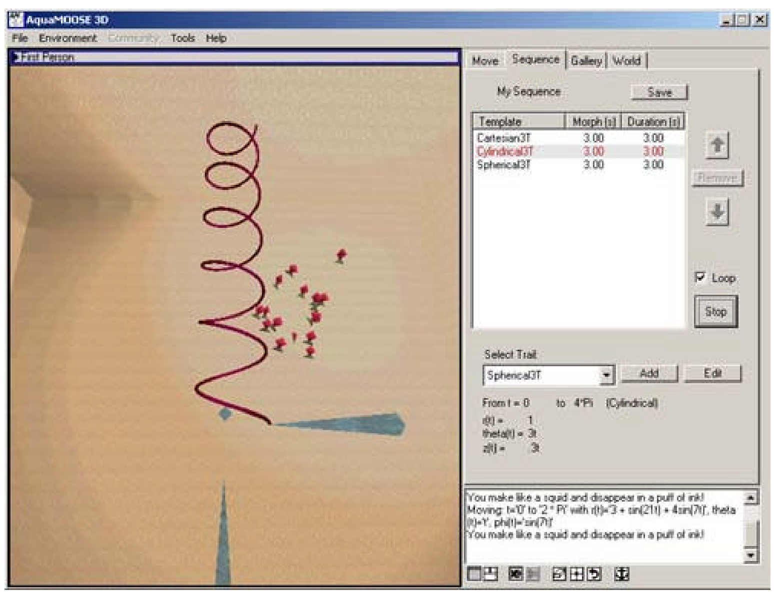


Figure 6.2: A trail sequence

Another new feature in this version of the software was trail sequences. Trail sequences allowed the participants to create a trail that morphed through a series of parametric equations (see Figure 6.2). This morphing could be synchronized to outside events such as audio streams or video streams, similar to visualization tools seen in popular MP3 players. Two values for each set of equations controlled the morph time and duration for that entry. The morph time determined how long it took the trail to morph to the appropriate equations. The duration of the entry was the amount of time before the sequence moved on to the next set of equations.

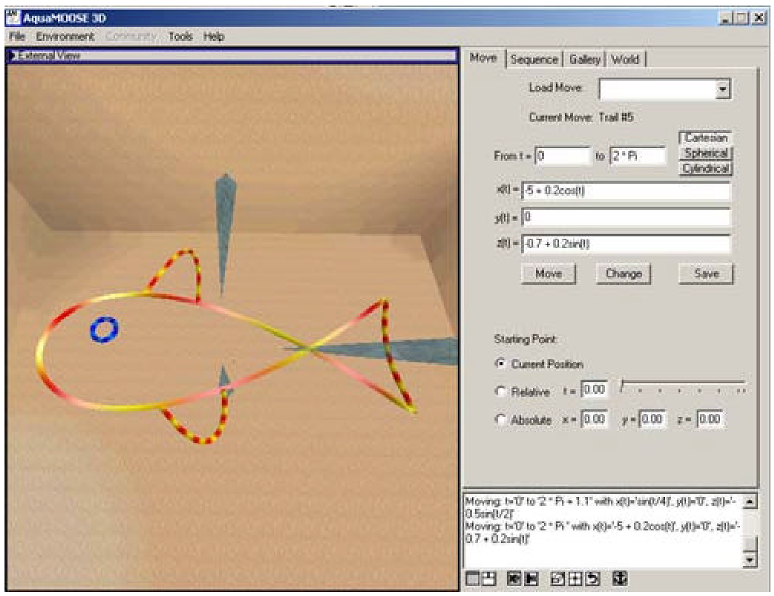


Figure 6.3: A fish created with 5 sets of connected equations

This final version of AquaMOOSE also included the ability to save multiple trails to form a more complex artifact. Sets of math trails could be created to form works of art. Trails could be colored and animated. Cameras could be positioned to show exactly what the student intended. All of this information was then saved into a single scene that could be quickly reloaded through the gallery interface. An example of a scene object might be a mathematical fish that has a body, fins, and eyes (see Figure 6.3). The body would be one trail, while each fin and eye would be a separate trail that is drawn relative to the body trail. Other examples of scene objects can be found in the description of five students' experiences during the after-school program study (see section 6.1.4 below).

The GHP and BHS studies showed that neither free-time use nor a classroom setting resulted in the type of motivation and engagement we had expected from the AquaMOOSE system. In the final study, we designed the social context as a middle ground between the two previous configurations. This study involved recruiting students from a local high school to participate in an after-school program that would be run by the researchers. Teachers were an important part of the recruitment phase of the study, but they were not required to teach content or to use the AquaMOOSE software. The goal we provided for the students was to create a portfolio of mathematical artworks to share with their family and friends. Participants who completed the program also received a certificate and the opportunity to display some of their creations on a website hosted by the researchers.

Some sessions during the after-school program began with a lesson on math concepts related to the AquaMOOSE software. Others began with descriptions and tutorials about using different features of the software. Once those presentations were made, the students had the remaining time to explore and create whatever they desired. This format gave students enough structure to support their learning process both with the software and with the math content, while allowing them enough freedom to control the exact direction of their exploration. Some students preferred to complete the program in a more structured fashion, following the challenges and suggestions provided by the researchers. Other students took a different path, using the software to meet their own personal goals rather than those provided by the researchers. One student used the software primarily to create rectangular and linear scenes, such as a basketball court and a volleyball court. Through the process of creating those artifacts, however, that student learned a great deal about 3D Cartesian coordinates and how to relate the X, Y, and Z axes to the 3D visual representation provided by the software. The diversity of use by a group of seemingly similar students in this study indicates that the semi-structured design of the social context is the best match for the type of constructionist learning environment we created in the AquaMOOSE project.

6.1 Thompson High School After-school Program

In this section, I discuss the third and final formal evaluation of the AquaMOOSE system. This evaluation took place during an after-school program at a local high school. Participants in the program were encouraged to explore combinations of math and art that they found to be personally appealing. The goal we provided for the participants was to create a portfolio of mathematical artworks to share with their friends and family.

I begin the section with an overview of the after-school program. Next I provide details about the study, including descriptions of the participants, the data collection method, and the data analysis that was performed. I then present the results from those analyses. The section concludes with a discussion of the results.

6.1.1 Study Overview

In the spring of 2004, I conducted an after-school program at a local high school, which I will call Thompson High School (THS), to explore issues of motivation in math learning. During this program, students used the AquaMOOSE 3D software to create mathematical artworks and share them with their friends. Five students completed the program. Each of those students took a different approach to the creative process and produced different types of artifacts (see Table 6.1).

Table 6.1: Some General Usage Patterns of the Study Participants

Name	Selected General Usage Patterns
Sarah	Replication of objects; Alternate goal formation resulting from challenges
Jackie	Random exploration; Frustration from lack of success
Cam	Focused creativity driven by prior goals; Exploration of 3D Cartesian coordinate space rather than more complex mathematics
Tong	Quicker project completion; Presentation of specific artistic ideas targeted at the viewing audience
Maria	Performance goal mindset; Suppressed creative exploration of complex math

One issue that came up on several occasions during the after-school program was the difference between representation and abstraction. We attempted to create the curriculum for the program in a way that supported both modes of creativity. However, including a challenge goal to create a representational object seemed to predispose all of the participants to a representational mindset. Several students, particularly Maria, made comments during the program about how their creations did not “look like anything” and were therefore not successful. As I discuss below, this conflict between representational and abstract creation evolved for several students during the final presentation. The presence of an audience helped the students to understand that both modes of creativity are valuable.

6.1.1.1 Research Questions

The THS after-school program study addresses two primary research questions (see Table 6.2). The first question is one that has been important throughout the entire AquaMOOSE project. How can we leverage the affordances of 3D graphical technology to improve students’ interest in mathematics? The second question focuses on the variety of ways students use constructionist learning environments and how their prior interests affect their usage patterns.

Table 6.2: Research Questions

- How can we improve student interest in academic subjects, specifically mathematics?
- What trajectories do students utilize in a constructionist learning environment and how do differences in prior interests affect those trajectories?

6.1.1.2 Hypotheses

We had four major hypotheses for the THS trial (see Table 6.3). The first hypothesis was that all of the participants in the after-school program would show improved interest in mathematics and art. The second hypothesis was that students who had a greater prior interest in one of math or art would show greater improvement in their interest for the other area. The idea behind this hypothesis was that the synergy designed into the AquaMOOSE system between math and art would give participants a base of prior understanding and motivation to leverage when learning about a new area. Our third hypothesis was that students who succeeded in creating personally meaningful artifacts would show greater improvement in interest towards math and art. The final hypothesis for the THS trial was that students with different prior interests would use the AquaMOOSE system in different ways. This diversity of usage provides more insight about the effectiveness of constructionist learning environments across many groups of participants.

Table 6.3: Hypotheses

• Most students' interest level in both math and art will improve (except those that are already high). The magnitude of this change is expected to be small but significant.
• A larger magnitude improvement in interest level will be seen in students who start off with much higher interest in one of (math/art) than the other. The lower area will improve more, because the environment helps the student leverage interest in one area to build interest in the other.
• Improvement in interest level will be positively correlated with improvement in portfolio scores and content tests (expertise).
• Students with different prior interests in either art or math will approach the program differently and follow different learning trajectories while creating their portfolios.

6.1.2 Technology Summary

The final version of the AquaMOOSE software includes several new features that reinforce the connections between math and art in the virtual environment. Ring games were eliminated from the interface and focus was placed entirely on mathematical trails as primary artifacts. Tools were added to allow users greater control over the visual presentation of trails. Coloring and animation properties were made accessible so that users could customize their trails in new and interesting ways. The ability to save the entire state of the 3D environment, which we call a "scene," was also added. Scenes allowed participants to present specific aspects of their creations by carefully positioning the trails and cameras within the 3D space (see Figure 6.4).

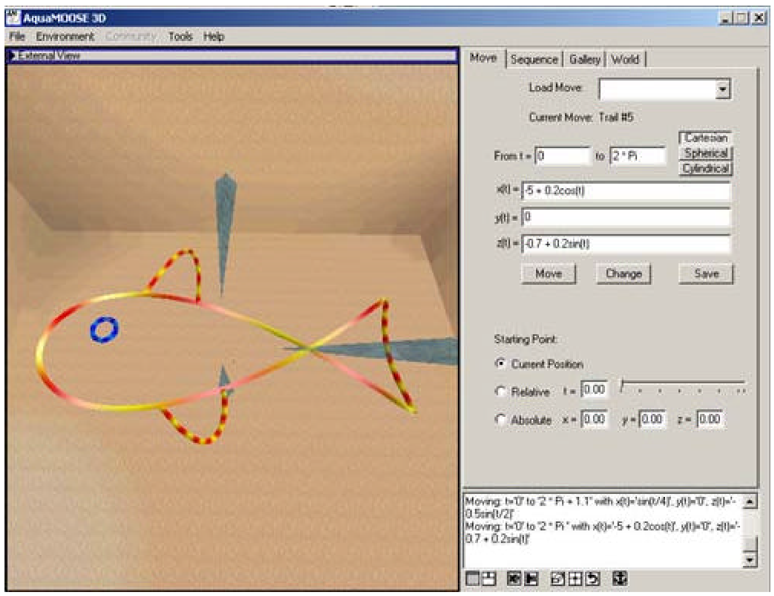


Figure 6.4: A scene created using the THS version of the AquaMOOSE software

Many usability features were added, such as the small “quick buttons” in the bottom right of the interface. These allowed certain menu functions to be accessed quickly and easily without obscuring the graphical portion of the interface. The menu structure was reorganized as part of the elimination of the Ring Game. Trail sequences were added to allow users to control morph sequences between sets of mathematical trails.

6.1.3 Method

6.1.3.1 Participants and Recruitment Method

Thompson High School has a population made up primarily of minority students (96.3% minority) with low socio-economic status (52% of students qualify for reduced or free lunch).

Forty-one percent of the school's students are enrolled in remedial education classes and the average SAT score for the school is 823.[2]

Though THS has a strong art department in addition to its strong math department, a lack of buy-in from the art faculty resulted in our primary interaction being with the math faculty and students. Students were recruited for the after-school program via software demonstrations in their math classes. After a brief explanation of the program and software, students were asked to complete an application form with some basic information about their interest levels in math and art. Flyers were also posted around the math department encouraging students to apply for the after-school program. The application process was intended to help us choose which students to accept and to give the students a sense of investment in their participation. Due to the smaller number of applications we received, we chose to accept all fourteen of the students who applied. Those students were provided with a set of consent forms and more detailed information about the program. Students aged 18 years or older were able to sign their own consent forms. Students under the age of 18 were required to complete an assent form and then have a parent or guardian complete the parental consent form. Nine students returned signed consent forms. Of those nine students, six came to at least one session of the program. One of those six students left the program after a few weeks due to time constraints. The experiences of the remaining five students are presented below.

6.1.3.2 Data Collection

During this evaluation, six types of data were collected:

- Interviews
    - Pre-interviews with each participant were conducted before the program began.

[2] Demographics based on the 2002-2003 school year

  - Post-interviews were conducted with four of the five participants. The fifth student declined to participate in the post-interview.

- Attitudinal Inventories – administered at the first and last sessions of the program
- Video recordings
  - Stationary video camera – recorded social interaction among students and researchers
  - Roaming camera(s) – captured individual creative episodes and interactions
- Observations – taken by each researcher present during the program sessions
- Log file data – record of every action taken in the AquaMOOSE software
- Artifact description documents – information provided by the participants about their creations
- Artifacts – the resulting mathematical artworks produced by the program participants

The pre-interviews give some basic information about each participant, including a general description of prior interests in both math and art. The post-interviews provide more insight into the learning experiences of the participants and how they feel about that experience. Attitudinal inventories were administered to supplement the interview and observation data in describing changes in participant interest levels over the course of the program.

Each of the eight study sessions was videotaped using two or three cameras. One camera was placed on a tripod and used to capture interactions between students and researchers. The other camera(s) were small hand-held cameras used to capture more detailed accounts of individual episodes with particular participants. Due to the small number of participants in the program, equal amounts of video were recorded for each of the five primary students. In addition to the video recordings, each researcher present during the study sessions took field notes that were shared with the group and compiled into a single document. To supplement these data sources during the sessions, the AquaMOOSE software captured all actions taken by the participants within the 3D environment. These log files show every iteration of math equation typed in by the students, in addition to any instant messages sent or presentation modifications made to artifacts.

When participants completed a mathematical artwork, they were asked to fill out a worksheet called an Artifact Description Document (see Appendix A.6). These documents provided the students with an opportunity to reflect on the creation process and to share their experience with others. Although the students were encouraged to complete a document for each artifact they created, only a handful of documents were returned to us throughout the after-school program. The artifacts themselves are the most important data source for this study. The completed works of each participant clearly illustrate the variety of approaches and learning experiences the students had in using the AquaMOOSE system.

6.1.3.3 Data Analysis

The analysis of this after-school program focuses on the individual experiences of the five students who regularly attended. Each of these students developed a personal style of creation over the course of the after-school program, which is evident in each student's portfolio of artifacts.

Three primary methods were used to analyze each participant's experiences during the after-school program. First, video data and log file data were used to recreate what each student did during the program sessions. The participant's experience was analyzed for each session and for the program as a whole. In this analysis, the recreated experiences provide insight into how the students' perceptions of math and art changed over the course of the program.

Second, the log file data was used to describe each participant's progression with respect to the underlying mathematical concepts. Help-seeking behavior is also used to highlight how the participants' conceptual understanding changed during the course of the after-school program.

Finally, the artifacts students created during the program are analyzed on an individual participant basis. The origin and evolution of each artifact was described using log files and Artifact Description Documents (when available). Each student used different strategies throughout the creation process, which are highlighted in this analysis.

6.1.3.4 Challenges

Throughout the after-school program, students were encouraged to choose creative projects that were appealing to them. However, we also provided the participants with particular goals that they could work toward if they were having trouble coming up with ideas of their own. These goals were called "Challenges" and were handed out during some of the after-school program sessions (see Appendix A.2 through A.5). Students were not required to complete any of the Challenges, and were not asked to demonstrate any progress on the Challenge activities. The Challenges were intended to provide students with a few ideas to help them get started on a project that would eventually lead them to develop new, more personally meaningful goals.

6.1.3.5 Program Schedule

The program met once a week for 90 minutes over an 8-week period. Sessions typically began with a brief introduction of either a math concept or software feature. The remainder of the time in each session was used for free exploration and creation using the AquaMOOSE software. Immediately after the final session of the program, students gave a public presentation of their digital artworks to friends, family, and teachers. Four of the five students participated in this public presentation session. What follows is a timeline of the after-school program sessions, including a brief description of each session.

Session 1 (March 4): The first session of the program was intended primarily to introduce the participants to the AquaMOOSE software and to each other. Challenge 1 “Circles and Leaves” (see Appendix A.2) was provided to give the participants an interesting task to focus on at the end of the session.

Session 2 (March 11): This session began with an overview of parametric equations and polar coordinate space. Challenge 2 “Making Spheres: Polar Coordinates” (see Appendix A.3) was used to reinforce the concepts discussed in the overview.

Session 3 (March 18): The third session allowed the students to work mostly on their own creative projects. The session consisted primarily of a brief introduction to and explanation of the larger goals for the next several sessions. The students were asked to begin working on an object to present during the informal critique session that would take place during Session 5.

Session 4 (March 25): Due in part to the school’s state testing for juniors and seniors, only a couple of students attended this session. Scene construction was introduced as the topic for the session and students were given a template Artifact Description Document (see Appendix A.6) to help describe and reflect on any objects they created.

Session 5 (April 1): The fifth session allowed each student to present an object he or she had created and to receive constructive feedback from the rest of the participants. Students were again asked to complete an Artifact Description Document (see Appendix A.6) to help them present their creations. After the informal critique, Challenge 3 “Trail Properties: Color and Animation” (see Appendix A.4) was given to the students to help them explore various aspects of the software that allow more creative expression.

April 8: THS Spring Break (no session).

Session 6 (April 15): This session introduced trail sequences and allowed the participants to continue building objects for their portfolios. Challenge 4 “Morphing Trail Sequences” (see

Appendix A.5) gave the students a chance to create an animated sequence where a caterpillar morphs into a cocoon, which then morphs into a butterfly.

Session 7 (April 22): The seventh session allowed students to work freely on their own creative projects. The format for the final presentation was introduced, and the students were encouraged to use Artifact Description Documents (see Appendix A.6) to help them reflect on the artifacts they had already created.

Session 8 (April 29): The final session of the program consisted of a normal 90-minute period as well as a formal presentation afterwards. During the first part of the session, participants focused on finishing their portfolios and preparing their presentations. Five participants attended the session; nineteen people attended the presentations.

6.1.4 Results

This section focuses on the experiences of five students during the AquaMOOSE THS After-School Program. The five students presented here are Sarah, Jackie, Cam, Tong, and Maria. Observations, video recordings, log files, and artifacts have been compiled into case studies for each of these participants. Through these case studies, we are able to better understand the variety of ways students were able to use the AquaMOOSE system. Each of these students represents a particular style of learning in the AquaMOOSE environment.

Each artifact that was created during the program was traced using log files. Artifacts were categorized based on origin, and the iterative changes made to the artifacts' underlying math equations were tabulated. Tracing the origin of each artifact provided information about the starting points students used to create objects in the AquaMOOSE environment and how our system supported a variety of learning approaches. Through our observations of the participants, we noticed that some artifacts were created completely from scratch whereas others were based on artifacts previously created by researchers or other students. The origin of each artifact was simplified into one of two categories to reflect that distinction: uniquely created artifacts (UCA) and non-uniquely created artifacts. UCAs were the result of independent creative activity that was not obviously traceable to any previous artifact or any particular event during the after-school program. Non-UCAs were built upon previous artifacts or were the result of specific direction from researchers.

The five students presented in this document attended between 4 and 8 sessions of the after-school program. The average number of commands[3] participants issued during each session ranged from 190 to 373. Students created between 6 and 25 artifacts with average iterations ranging from 12 to 32.6. See Table 6.4 for a summary of the students' participation.

Table 6.4: THS Participation Data

Participant	Sessions Attended	Avg. Commands per Session	Total Artifacts	UCAs (Unique)	Avg. Iterations per Artifact
Sarah	7	373	17	10	32.6
Jackie	5	200	11	4	29.4
Cam	6	298	6	3	30.2
Tong	4	190	13	2	12
Maria	8	259	25	4	12.4

The five participants whose experiences are presented here all succeeded in creating visually appealing mathematical artifacts using the AquaMOOSE system. They explored different types of math and presented different styles of artwork. Each case begins with a brief overview of the participant and his or her activity during the THS program. Then a detailed account of each session is provided to show how the participants' experience evolved throughout the program. Each case concludes with a summary and brief analysis.

[3] Commands issued includes manipulations of mathematical artifacts such as changing the equations or the colors of the trail, moving the artifacts around in the Gallery (see Section 1.4.2.3), or changing environment parameters like camera placements.

6.1.4.1 Case Study #1 – Sarah

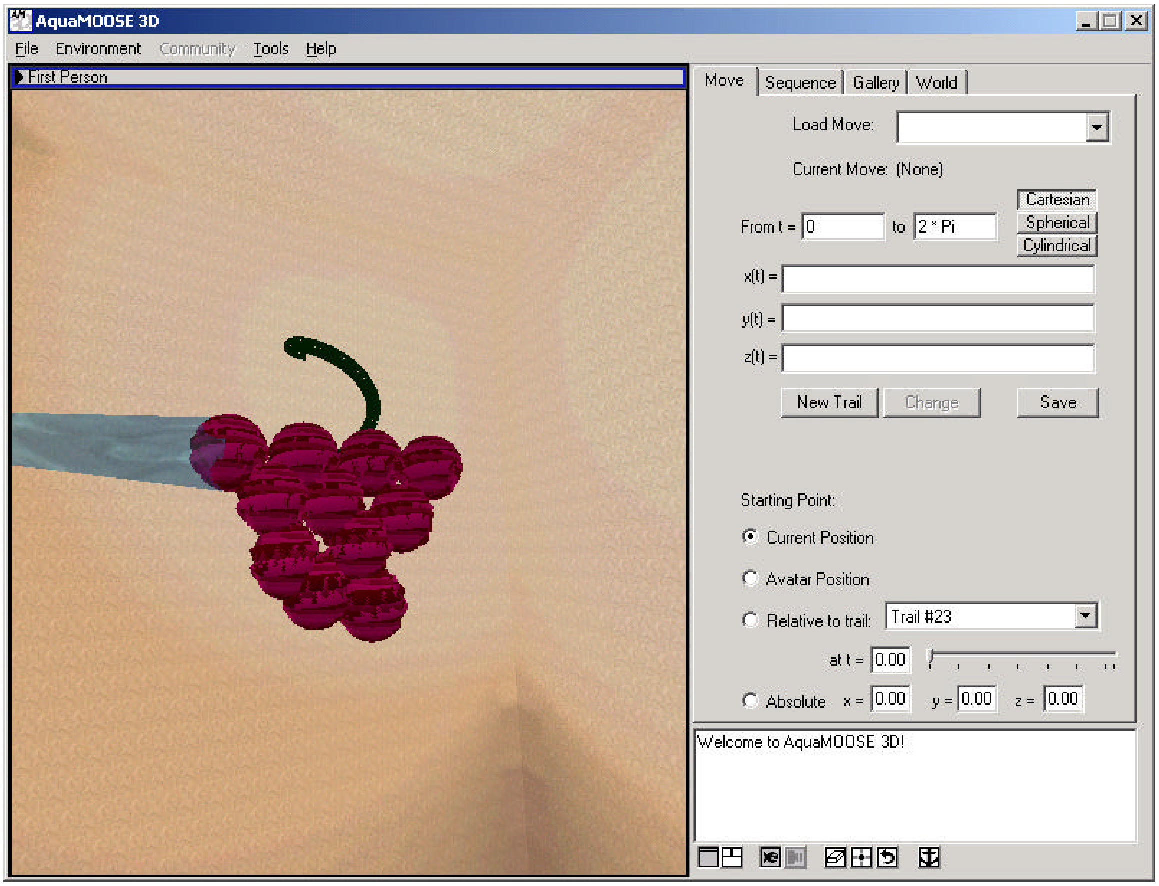


Figure 6.5: Sarah's "Grapes"

Sarah is an African-American female in the 12th grade. Sarah declares herself as primarily a math student. When asked about her favorite subject, she responded, "Math, because [the] majority of the topics and procedures come naturally to me." Sarah tutors other students in math at school and in her home. She also enjoys teaching herself how to use different software applications, and wants to study computer science in college. She applied to participate in the AquaMOOSE after-school program because she was interested in creating representational objects with the software: "I was very interested because I really want to see what I can make, like what objects I can make… the fish was real cute… the little palm trees… I want to see what I can make."

Sarah was almost always the first student to arrive at the after-school program, and was present for all of the sessions except one (session 4). Many of her objects involve replicating smaller objects to create a larger scene. Sarah developed artistic goals for her creations earlier than some of the other participants. When she happened across the equations for a vertical circle during one session, she quickly decided that she wanted to make the Olympic rings. Likewise, when she came up with the equations for a small sphere in the process of solving a Challenge, she decided she wanted to replicate it to create a bunch of grapes (see Figure 6.5).

6.1.4.1.1 Session One

Sarah was the first student to arrive for our first program session. She told us that she was expecting a friend to come as well. Her friend, who did not complete the program and is not described in this thesis, arrived soon and sat down next to her. Some of the computers were not able to connect to the Internet, however, and Sarah's friend ended up moving to the other end of the row while Sarah stayed behind with empty computers on both sides of her. Sarah seemed to enjoy learning how to use the AquaMOOSE software. She often moved ahead, trying out features before they were described.

She worked on the challenges that were handed out. At one point while working on the Cloverleaf challenge (see Appendix A.2), she created an interesting looking flower and wanted to show it to the other students. She turned to Tong, who was sitting two seats to her right, and said, "Hey, look at my flower!" Tong's response was not very enthusiastic. Sarah was a little disappointed by his reaction, so one of the researchers reminded Sarah that she could save her flower and then send an IM to her friend across the room. Sarah had already brought up the IM window and was about to do exactly that. This resulted in a brief IM conversation between Sarah and her friend about Sarah's new flower.

6.1.4.1.2 Session Two

Before the lecture portion of the second session, Sarah logged into the AquaMOOSE software and began playing with trails. She was eager to try out the software again and seemed to have more ideas about what she wanted to create.

While working on the Sphere challenge (see Appendix A.3), Sarah ended up with something that resembled a Hershey's kiss (see Figure 6.6). After iterating through 25 different sets of equations, she decided that it was complete and saved it. Not only did she save the move, but she also spent some time trying to adjust the color and other properties of the trail to make it look more genuine.

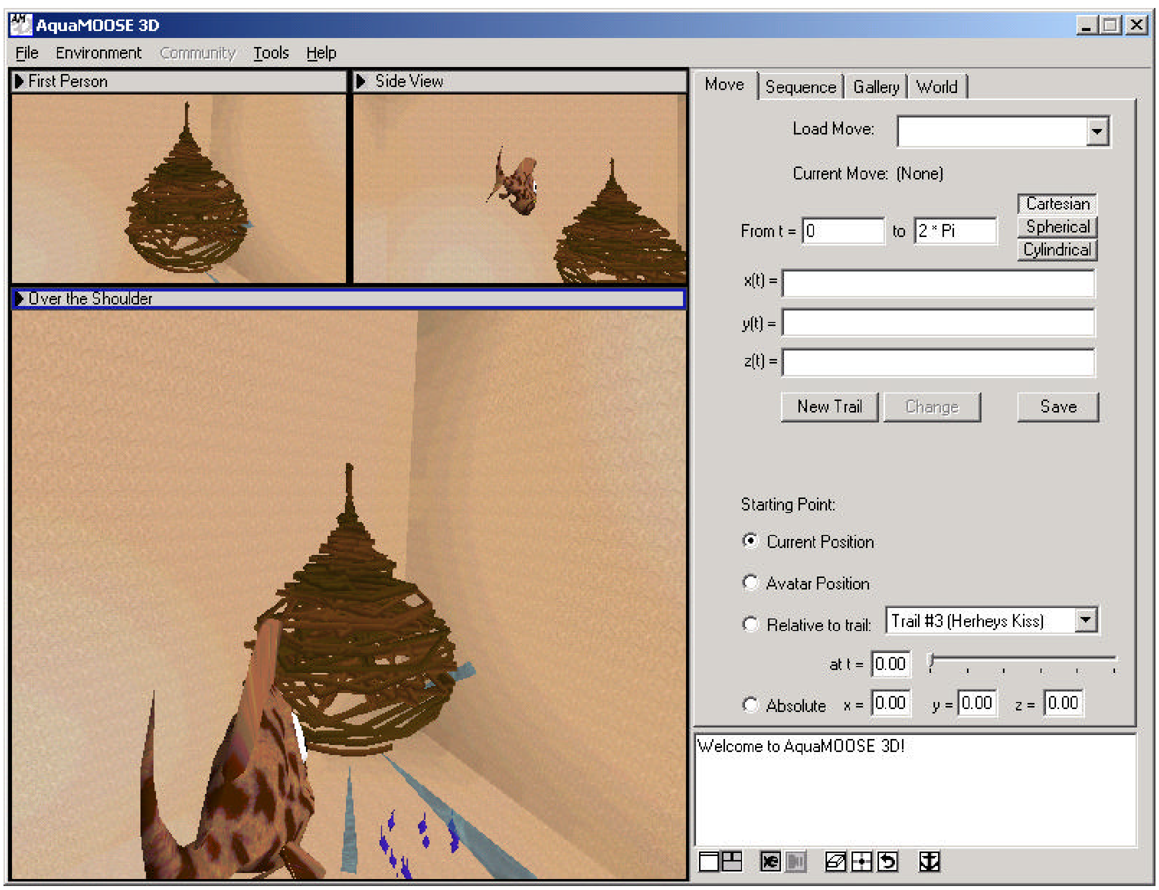


Figure 6.6: Sarah's "Hershey's Kiss"

6.1.4.1.3 Session Three

During the third session, the participants were instructed to begin working on a “still life” type project. Some sample artifacts were presented as starting points and examples. Sarah played around with the palm tree and a few other samples, but did not work on them for very long.

At one point, she loaded and explored a set of three saved moves that use identical equations in each of the three different coordinate spaces. She tried to use these equations to understand the differences between Cartesian, cylindrical, and spherical coordinate space.

Towards the end of the session, Sarah created a vertical circle shape and told us that she wanted to create the Olympic rings. She worked on this project for the remainder of the session. After spending some time trying to line up the rings in the appropriate fashion, one of the researchers helped her figure out how to use absolute coordinates to place the rings exactly where she wanted. She placed the three upper rings, but then was unsure about how to place the two lower rings. She took out a piece of paper and sketched out the Olympic rings to remind her of how they should be positioned. Then she came back to the AquaMOOSE software and finished placing the other two rings. Once she had the rings positioned, she decided she wanted to color them. Instead of using the standard Olympic colors, she created a gold color using the custom palette and painted all five rings that color (see Figure 6.7).

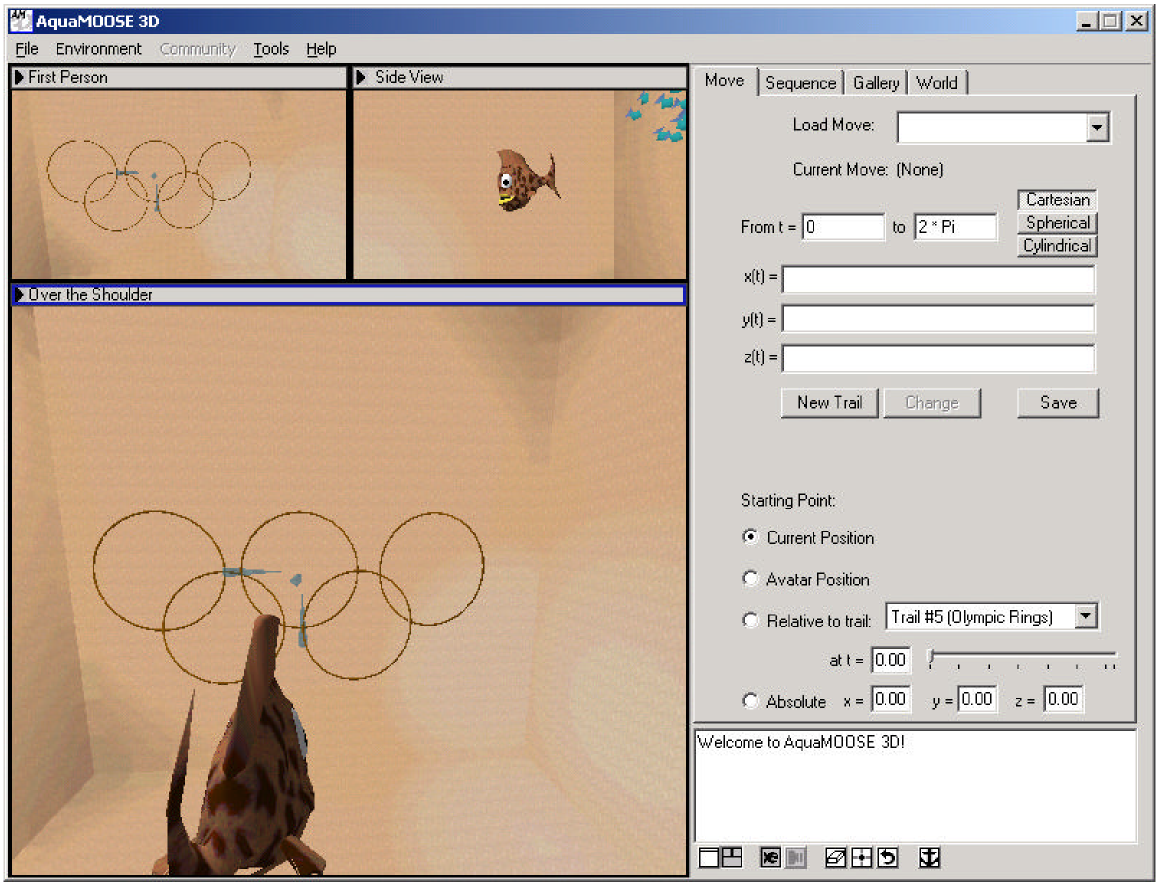


Figure 6.7: Sarah's "Olympic Rings"

6.1.4.1.4 Session Five

Sarah decided to present her Olympic rings artifact during the informal critique session. When she created it in session three, the software had been unable to save all of the rings positioned and colored in the way Sarah wanted. She had been able to save only one of the rings. At the beginning of the fifth session, she recreated the entire Olympic rings scene, including the color and positioning, in just a few minutes. She remembered how she had done it two weeks ago and was able to do the same things again with ease.

The other students did not have many comments about Sarah's Olympic rings, other than the fact that it looked interesting. The researchers tried to provide her with suggestions about improving the scene or adding more features to it, such as a water fountain or other symbol of the Olympics.

Sarah spent the rest of the fifth session working on the Tornado challenge.

6.1.4.1.5 Session Six

Sarah began the sixth session by working on the Butterfly challenge. As she worked on her caterpillar trail, she performed what appeared to be random manipulations in an attempt to create more “bulbs” or body sections for the caterpillar. She selected coefficients at random and added more and more components to her equations in the hopes that “more complex” would equal “more bulbs.”

At one point, she went through her equations and placed a decimal in front of any coefficient. In other words, a 9 turned into 0.9, a 43 turned into 0.43, and so on. This had the effect of basically nullifying all of the components in the equations, which resulted in a decidedly less bulbous trail. She quickly undid the changes and went back to her other methods of changing the equations.

Sarah eventually realized that the complex equations were not giving her what she wanted, so she scrapped them and went back to a more simple set of equations. This time she started working on the cocoon for the challenge. At some point while working on the cocoon, however, she ended up with a small, dense sphere and decided she wanted to use it for something else.

She began replicating the small sphere. At first, she replicated the sphere in the exact same location and did not realize she had created so many of them. With some help, she was able to select each copy of the sphere and move it to a new location. She informed the researchers that she was making a bunch of grapes. She colored all of the grapes purple and continued arranging them until she had an assortment that resembled a bunch of grapes. She finished off her project by adding a green stem to the top of the bunch (see Figure 6.5 above).

6.1.4.1.6 Session Seven

Sarah spent most of the seventh session working on her portfolio in preparation for the final presentation session. She created a new trail that closely resembled a head and face. The researchers were impressed with the face and encouraged Sarah to complete it and add it to her portfolio. However, Sarah became frustrated when she was unable to get the hair on the head to look the way she wanted. Instead of continuing to work on the project, or saving it to work on later, she simply cleared the whole screen and moved on to something else.

At several points during this session, Sarah looked over at the other students' computer screens to see what they were working on. None of the other students noticed Sarah looking, and Sarah never asked any of the other students about their work. This is one of the few instances throughout the program where a student seemed interested in what the other participants were doing. Most of the time, all of the students concentrated on their own work and did not pay much attention to the other students' activities.

Sarah left the session early.

6.1.4.1.7 Session Eight

Like the other participants, Sarah spent the beginning of the eighth session preparing for the final presentations. She set up all of her moves as scenes and did some polishing work with colors and trail properties.

Sarah introduced herself at the presentation as a more artistic person than she had described herself as previously. She said that she likes to draw and wanted to see what kind of things she could make with math.

Sarah's presentation was impressive. Of all the participants, she was most comfortable standing up and talking to the audience. She presented her tornado, bunch of grapes, pyramid, Olympic rings, Hershey's kiss, flower, and a morphing sequence that required viewing from a certain angle to see the "beauty" of it. Sarah's mother also attended the final presentation session.

6.1.4.1.8 Case Analysis

Sarah declined to participate in the final interview of our study, but her work throughout the after-school program shows that she took pride in the things she created with the AquaMOOSE software and was excited to share them with her friends. She spent most of her time working on the challenges, and used them as a starting point to come up with other project ideas.

The Hershey's kiss project shows a clear motivation from the beginning of the program on Sarah's part to create concrete and recognizable objects. Her attention to the details about the object indicates that she considers it to be a final product to be shared with others, not just a random digital creation that can be easily discarded.

Sarah's "Olympic Rings" project is an example of her goal-driven personal style. After creating a simple ring, she decided that she wanted to make this artifact and then pursued it exclusively until it was complete. Through the process of creating this artifact, she learned how to use absolute coordinates in 3D to place objects relative to other objects. Her use of color and attention to detail again illustrates her belief that the artifact is a real work of art – something that she takes pride in and wishes to complete to the best of her ability.

Sarah used the challenges both as a goal in themselves and as a starting point for other projects. Several times during the program, her work on the challenges spawned other projects that were more interesting to her. Her "Grapes" project began as a result of her work on the Butterfly challenge. While attempting to create a cocoon for that challenge, she decided that the small sphere she created looked more like a grape. Once she had that realization, she abandoned the challenge and pursued her personal goal of creating a bunch of grapes.

Sarah represents a group of students who are able to form their own personally meaningful goals given some scaffolding and examples. Many of the artifacts she created during our program were the result of this type of goal formation. While working on a Challenge provided by the researchers, Sarah discovered a new goal based on some of her intermediate creations. In some cases, she abandoned the original challenge to focus solely on her new project, but in others she completed the challenge and then pursued her new goal.

6.1.4.2 Case Study #2 – Jackie

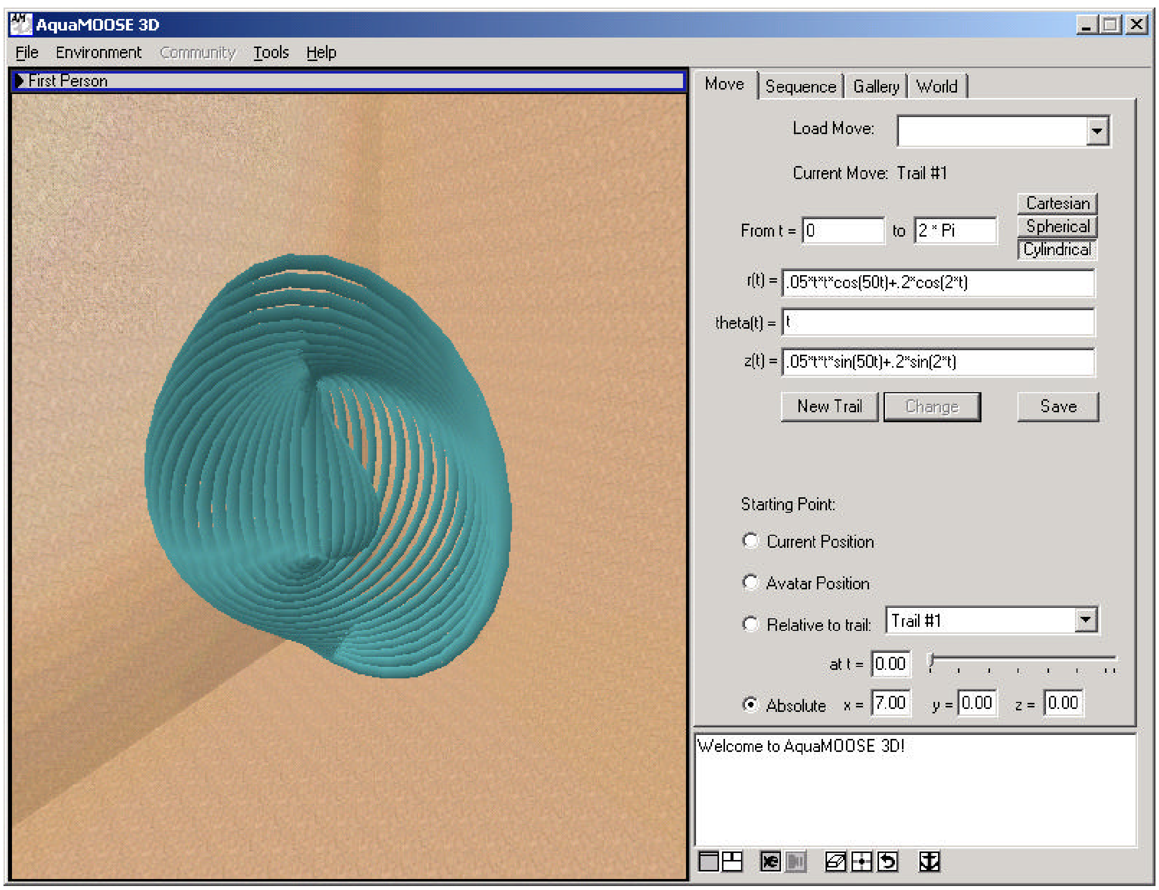


Figure 6.8: Jackie's "Seashell"

Jackie is an African-American female student in the 12th grade. Her primary interest is in using technology to design and create graphics, which she considers to be a form of art. She says, "I don't know how to draw or paint, but I still consider myself to be an art person because computer graphics is considered to be a type of art." Math is not one of Jackie's "strong points," but she still did fairly well in school math classes and took Calculus in her senior year of high school. She is interested in exploring computer-aided design and joined the program in order to get more experience with computers. Throughout the program, Jackie developed a personal style resembling the bricolage approach to construction (Turkle & Papert, 1991). She used and manipulated math equations in random patterns to try to create visually appealing artifacts.

Jackie seemed to get frustrated when she couldn't achieve the artistic goal she had in mind. The more frustrated she got, the more random her approach to changing the math equations became. However, not all of her random explorations of the math were due to frustration. She also exhibited curiosity about manipulations of the mathematics. She says, "Most of the time I was just trying to see what would come out with my equations that I put in, because I haven't really got down to the logic. That's why I really wished [the after-school program] was a little bit longer so I could get the logic of which equations do what."

Jackie also used her imagination to fill in missing spots in her artifacts. She created an object called "dome" that was actually missing part of the dome. She intended to go back and fix the artifact so that it actually was a dome, but she never got the chance to do so. She missed several sessions of the program (sessions 1, 4, and 6), so the amount of time she had to invest in her creations was less than some of the other students. In the last session, she asked the researchers what was on the schedule for the following week, and was disappointed to find out that the program was finished.

6.1.4.2.1 Session Two

Jackie spent the second session catching up to the rest of the participants. After she completed the surveys and was given a brief recap of the software introduction from the previous session, she began working on the Sphere challenge. She was quiet throughout the session and seemed to feel awkward, possibly because the other students had a head start and were already comfortable with the AquaMOOSE software.

Jackie's exploration in this session did not result in many visually appealing artifacts. She made good progress on the Sphere challenge, but was not able to generate interesting alternate effects like the other students. Amy suggested that Jackie try cylindrical or spherical coordinate space instead of Cartesian, but Jackie still had difficulty coming up with more appealing mathematical trails.

Due to a physical disability in her right hand, Jackie uses the mouse with her left hand. She also uses her left hand to type in equations and messages with the keyboard. As a result of this repositioning, Jackie's interaction with the software is somewhat slower than the other students.

6.1.4.2.2 Session Three

Jackie began the third session by loading the "Wicker Basket" trail provided by the researchers and manipulating the equations used to create it. On several occasions, she forgot to include parentheses in her trigonometric functions, which resulted in error messages from the software that she did not understand. Some assistance from the researchers helped Jackie figure out what she was doing wrong.

At one point during the session, Jackie accidentally deleted all of her trails. She was able to retrieve the trails once we explained the undelete features in the AquaMOOSE software. Jackie seemed to be less familiar with computer software than some of the other students, which resulted in some frustration on her part when the software did not perform the way she wanted it to. Later in this session, Jackie created a trail and morphed it out of the virtual world via a bug in the software. Once the trail was outside of the world, it was impossible to bring it back into the usable space. Jackie was reluctant to accept that the trail was unusable, however, and continued to try to morph the trail back into the world for several more minutes.

Jackie did not seem as engaged as the other students during the session. As she was leaving, though, she asked how she could use the software from home and transfer the things she created back to her account at school.

6.1.4.2.3 Session Five

During the fifth session, the students presented one of their artifacts to the rest of the group and received constructive feedback. Since Jackie did not attend the previous session, she spent the beginning of the fifth session preparing an artifact for the critique presentation while the other students worked on the Tornado challenge.

When one of the researchers presented one of his artifacts as an example for the critique session, Jackie asked him how he had chosen and applied the colors to his trail. Jackie presented two trails during the critique session, “bubble” and “star.” During her presentation, she realized that her bubble was missing its bottom half and decided to rename it “dome” (see Figure 3.11). She covered her mistake by saying that she really liked the “star” better and shifting her focus to it instead.

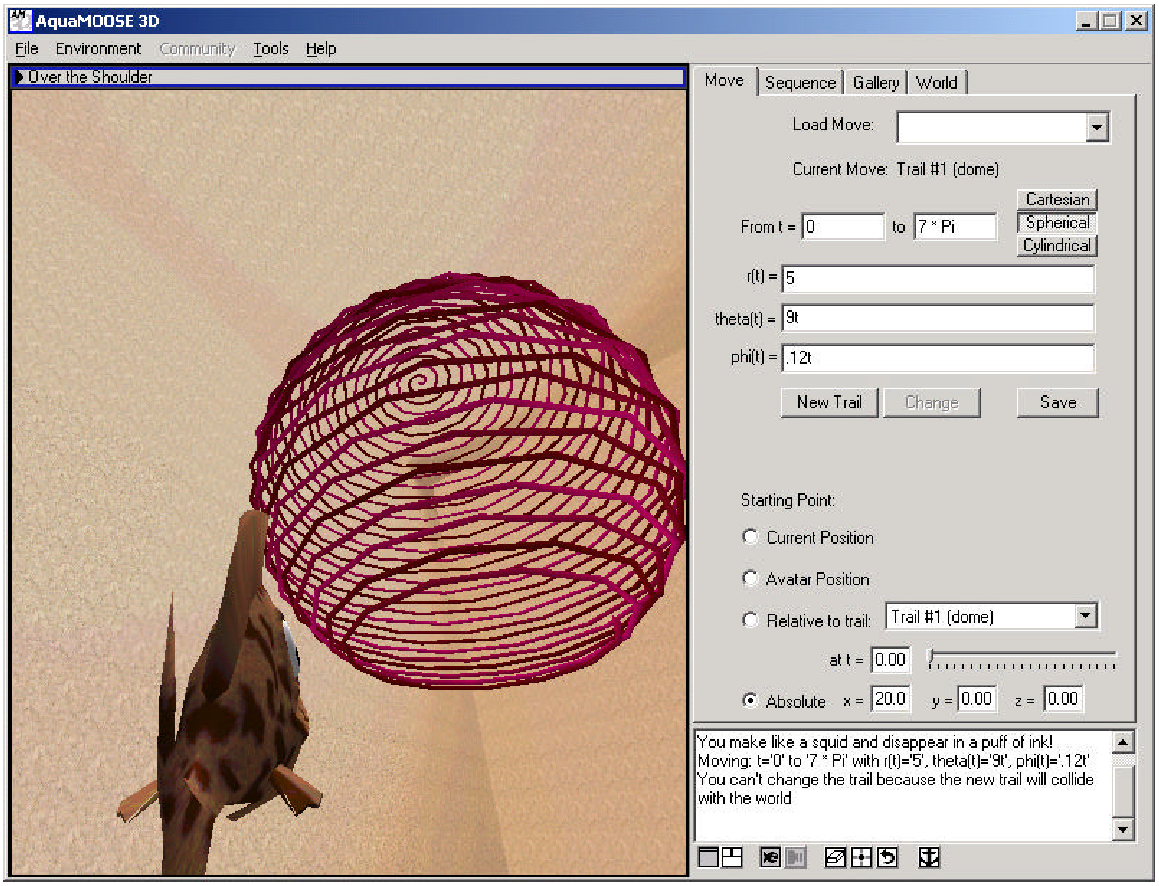


Figure 6.9: Jackie's "Dome"

After the critique presentations, Jackie began working on the Tornado challenge. She asked for help on several occasions, and eventually ended up with a trail resembling a nautilus that she derived from the tornado equations. She spent a lot of time working with the nautilus trail, and was pleased that she had created something visually appealing.

6.1.4.2.4 Session Seven

Jackie began the seventh session by asking what had been covered during the previous session. She had also sent me email asking the same thing, which I had responded to with a lengthy summary of the sixth session. I went over everything I had described in the email and then introduced the Butterfly challenge.

During her work on the Butterfly challenge, Jackie created a complex trail and began manipulating it by changing only the “to” value. Trails are created by evaluating the set of equations for values of the parameter ‘t’ ranging from a “from” value to a “to” value. Jackie began manipulating the “to” value by typing in random numbers, such as 123. She also had numerous 0’s before the 123, which had no effect on the trail but made the edit field difficult to read. Jackie spent a long time making small changes to the “to” value, most of which did not affect the visible trail due to the cyclic nature of trigonometric functions. Jackie was frustrated by the lack of impact her changes had, and often clicked the morph button numerous times thinking that the software must not have registered her changes.

After all of the students were set up to work on the Butterfly challenge, I showed Jackie how to use trail sequences. As I walked her through creating a sequence, she seemed excited about creating one of her own. After my explanation, however, she ignored trail sequences and never used one again.

Near the end of the session, Jackie began working on a pool table scene to show during the final presentation session. Through random exploration, she came up with a rectangular table artifact that spawned the pool table idea. She tried to add cue sticks to her scene, but was unable to position them in appropriate ways relative to the pool table. I tried to help her, but was also unable to make the cue sticks point at the table in a natural way. I informed Jackie that I would work on it after the session and get another researcher to help as well. Jackie left the session frustrated.

6.1.4.2.5 Session Eight

Jackie continued working on her pool table scene at the beginning of the eighth session. The researcher who I had talked to previously about Jackie’s pool table helped her position her cue sticks appropriately. She worked quickly to prepare her presentation because she had to leave early. She also seemed to be sick and left the room on one occasion due to a bad cough.

Jackie presented her creations before the official presentation session began, so only a few students and teachers were there. She was nervous and did not know what to say. After some prompting, she talked about learning the different coordinate spaces and then showed three of her artifacts. The first artifact she showed was her “seashell,” which seemed to be her favorite creation (see Figure 6.8 above). She was excited about the aesthetic appeal of the trail and took pride in the fact that it was something she made entirely from scratch: “The seashell… that was my best because I did that all by myself. It like wrapped and it came out.” Next she showed the pool table scene that she had worked on earlier in the session (see Figure 6.10). She said it was her most difficult creation. Her final artifact was her “star,” which she described by saying, “I put in some equation just to see what would happen, and kept it cause it looked nice.”

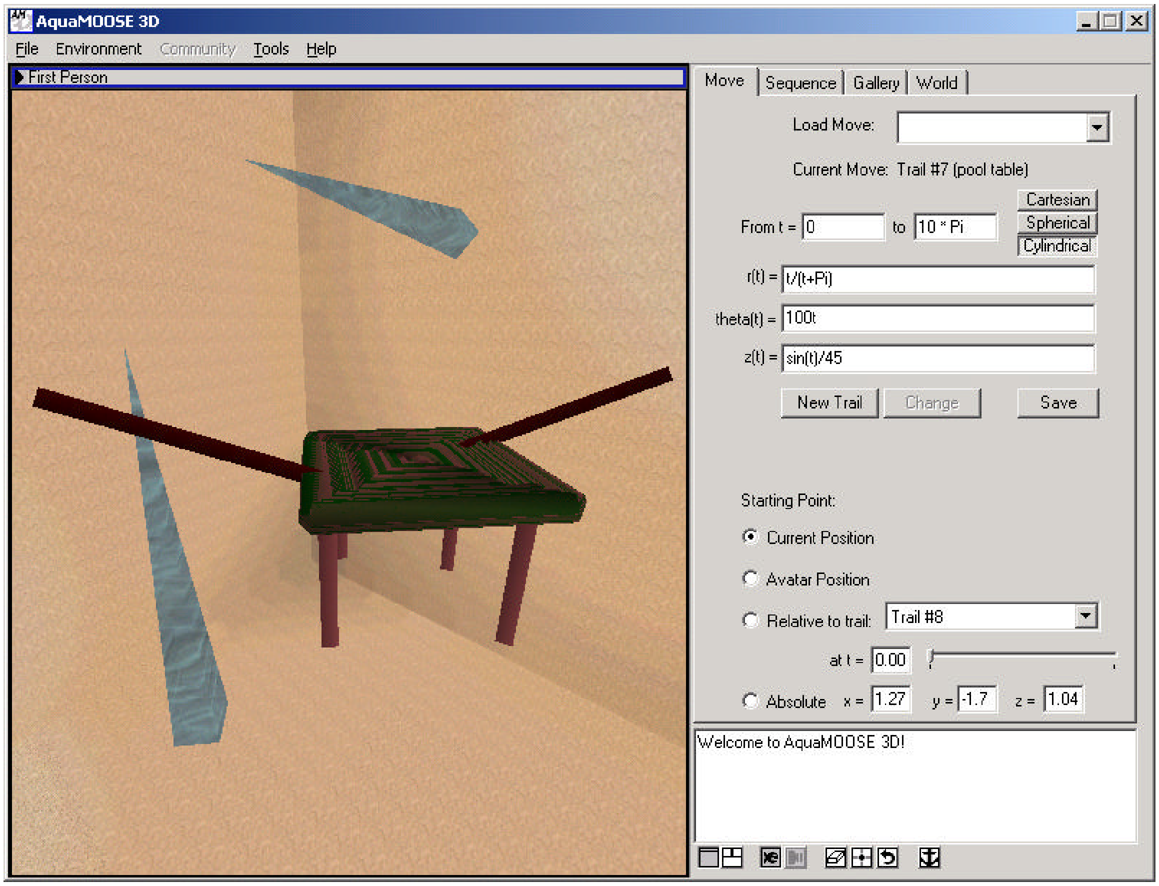


Figure 6.10: Jackie's "Pool table and stick"

6.1.4.2.6 Case Analysis

Jackie showed less outward enthusiasm throughout the after-school program. She had more difficulty achieving her goals with the software than the other students, which resulted in a lot of frustration for her. Despite her outward appearances, though, she asked for help more often than any other student and was the only student who seemed interested in using the software outside of the after-school program.

Jackie was more interested in creating visually appealing artifacts than exploring math concepts, but was unable to succeed in many cases. She says, "I came more for the art, but the math also drew me in." Her less developed understanding of the underlying math led her to use random manipulation more often than not. At several points during the program, this random manipulation succeeded in producing visually appealing artifacts like the “seashell” and the “star,” but it usually ended up resulting in frustration for Jackie instead. Jackie’s frustration was due also in part to the user interface, which did not always provide enough scaffolding and support for Jackie to achieve her goals.

6.1.4.3 Case Study #3 – Cam

Cam is an Asian male student in the 10^{th} grade. He is younger than all of the other participants in the program, and seemed somewhat intimidated by them. He spent most of his time interacting with Tong, an older participant who he knew before the program started. He knew some of the other students, but spoke little with them. He declared himself as a math person, but also seems to be at least moderately art-inclined and enjoyed showing off his work to Tong. He said, “I’ve only been to one art class but I consider myself pretty well in it.”

Cam began his participation in the program by creating larger-scale, or macro, scenes. His first creation was a basketball court. He used straight lines almost exclusively to draw the court boundaries, basketball poles, backboards, hoops, and surrounding arena. He inquired about how he could make a wall, and was provided with a high-frequency sine wave that approximated a solid wall. He then began using walls to define his spaces. Later in the program, he used similar techniques to create a volleyball court (see Figure 6.11). The mathematics Cam used was very simple. He did not seem interested in exploring alternative math equations. His primary focus was on building the scene from an artistic perspective. When asked what he thought could be added to the AquaMOOSE system, he indicated that he would have liked more templates for creating generic shapes so that he could use those to build larger artifacts:

> If the program had more stuff that can actually… in the program you have to figure out different equations, cause it’s challenging trying to figure out different

equations… like if you want to make a circle or something you have to go through and experiment and stuff like that. I guess tutorial stuff.

Towards the end of the program, Cam became busier with other extra-curricular activities and ended up missing the 6th and 7th sessions. He played in the school orchestra and missed those sessions to attend rehearsals and concerts.

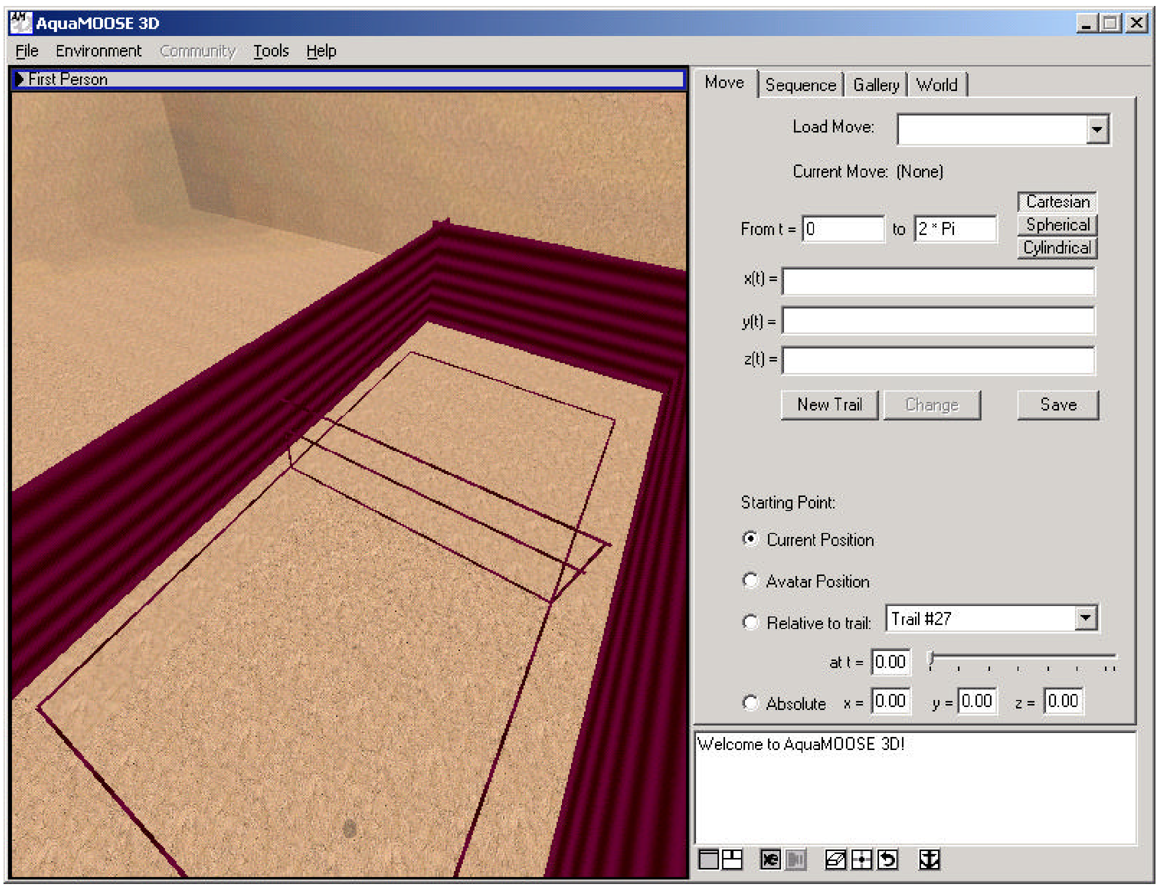


Figure 6.11: Cam's "Volly"

6.1.4.3.1 Session One

Cam used the first session to get familiar with the AquaMOOSE software and to explore the various 3D worlds that are included with the software. He navigated through tunnels and other features of the worlds while other students worked on the mathematical challenges. He also worked on the challenges with the other students, but seemed to be more interested in assuming the perspective of the fish avatar and understanding the 3D space.

At one point, Cam created a simple circle trail aligned vertically in the 3D space. As the fish avatar swam through the circular trail, Cam tilted his head up and down mimicking the avatar's rotation as it passed the bottom and top of the trail. He repeated this exercise two more times. This connection with the avatar and the 3D space as a whole became more apparent in Cam's creations throughout the after-school program.

Cam was the only student who noticed and seemed uncomfortable with the video cameras. The other students ignored the cameras, but Cam turned and looked directly at the camera on at least one occasion. At the end of the session, Cam was the only person who closed the software and got up to leave quickly. Everyone else remained engaged with the software and the tasks they were working on at the time.

6.1.4.3.2 Session Two

Cam listened carefully to the presentation about parametric equations and polar coordinates, but seemed a bit lost like the other students. After the presentation, he spent the majority of the remaining time on the Challenges. At one point while working on the Challenge, Cam took a break and just swam around in the various 3D worlds again. Then he went back to working on the Challenges.

Cam said that he had tried out the software from home, though the logs did not show any online activity. It is possible that Cam used the software offline, but I believe he was just trying to seem interested by saying what he thought the researchers wanted to hear.

6.1.4.3.3 Session Three

Cam started the third session by exploring some of the moves in one of the researcher's trail folder. Like Tong, whose experience is described later, Cam spent some time looking at the teacup and saucer trail. Cam was more interested in expanding the cup vertically, using exponents. He also tried to create a wisp of steam, similar to what Tong created, but ended up with a more jagged line that looked like a cloud of smoke instead of a wisp of steam.

After playing with exponents to stretch the teacup vertically, Cam watched his fish avatar spiral upwards through the trail several times. This led to Cam exploring vertical spiral trails in more detail. He created several iterations and watched his avatar move through them until it hit the top of the world.

Later in the session, Cam asked one of the researchers how to make a straight line. The researcher explained how to use Cartesian coordinates to make lines along different axes as well as diagonal lines. I noticed later that Cam had created what looked like a square. When I asked him how he made it, he explained that it was just four straight lines, but it was not a square. He moved his avatar back some to reveal a rectangular basketball court with vertical spiral columns at both ends and an arena surrounding it. Another researcher asked Cam if he was going to make backboards. Cam said he had a backboard but he accidentally deleted it and was trying to recreate it. Unfortunately Cam was not able to recover the backboard trail before the end of the session, but he did capture a movie of the basketball court and saved it to his network drive.

6.1.4.3.4 Session Four

Cam began the fourth session by creating a volleyball court that closely resembled his basketball court from session three. He used straight lines exclusively to draw his volleyball court and net. He then asked the researchers how he could make a wall. After high-frequency sine waves were explained to him, Cam used those to draw walls around his volleyball court. Later in the session, Cam cleared all of his trails and began working on a different project. I asked him if he had saved his volleyball court, to which he responded, “I forgot.”

The next project Cam worked on was a house created using the wall trail he had learned earlier. Cam tried to line up all of the walls and corners by positioning his fish avatar in the appropriate spot manually. As he drew all of the wall trails, he moved his head around in the physical world trying to “see” the virtual space more clearly. We explained to him that he could use absolute coordinates to place trails at exactly the right spot without having to guess. We also showed him how to morph existing trails when he was doing fine manipulations, rather than deleting the existing trail and creating a new one from scratch. He tried both of those suggestions for a few minutes, but then reverted to his old method of placing and refining his trails.

Cam continued to be uncomfortable with the video cameras, especially since there were only two students at this session. When the small video camera was turned off at the end of the session, Cam said, “Yay, I’m free!” Then he realized that the stationary camera at the back of the room was still recording, and was clearly disappointed.

6.1.4.3.5 Session Five

The fifth session was the critique session where students presented one of their artifacts and received feedback on it from the rest of the group. Cam did not have anything prepared to show, so he spent the beginning of the session recreating his volleyball court from the previous session. After we reminded him of how to make walls and use absolute coordinates, he quickly remade the volleyball court and presented it to the group. Most of the other students were impressed with his creation and gave him positive feedback about it. The researchers suggested that he could add other features such as volleyballs or players and fans around the court. Cam had to leave the session early.

6.1.4.3.6 Session Eight

Cam showed up early for the last session, along with Tong. Cam loaded up the video of his basketball court and showed it to Tong. He then showed Tong his other creations, including the volleyball court that he had finally saved during the fifth session. Cam then spent the remainder of the session preparing for the final presentation.

Cam began his presentation by showing the volleyball court. He navigated around the scene to show the audience how the court was situated in the 3D space. He was shy during his presentation, but the audience was impressed with his artistic ability. After his volleyball court, Cam tried to show another trail he had been working on that was supposed to add bleachers to the arena around the court. However, the trail did not look like he intended and he was unable to recreate the appropriate equations on the fly.

Cam concluded his presentation by showing a fountain scene that he had just created moments before the final presentation began (see Figure 6.12). Amazingly enough, this scene consisted of three trails, none of which were straight lines or walls! After spending the entire after-school program creating straight lines and walls, Cam began to explore curves. The fountain came about, however, as an unexpected result of Cam's continued efforts on his volleyball court. Cam was attempting to add stadium stands around his volleyball court, but failed to create the effect he desired. When a researcher noticed the new trail and gave Cam positive feedback about it, Cam was surprised and decided to make the trail into a new project. He added a couple more trails to the scene to create a water fountain and decided to show it during his final presentation.

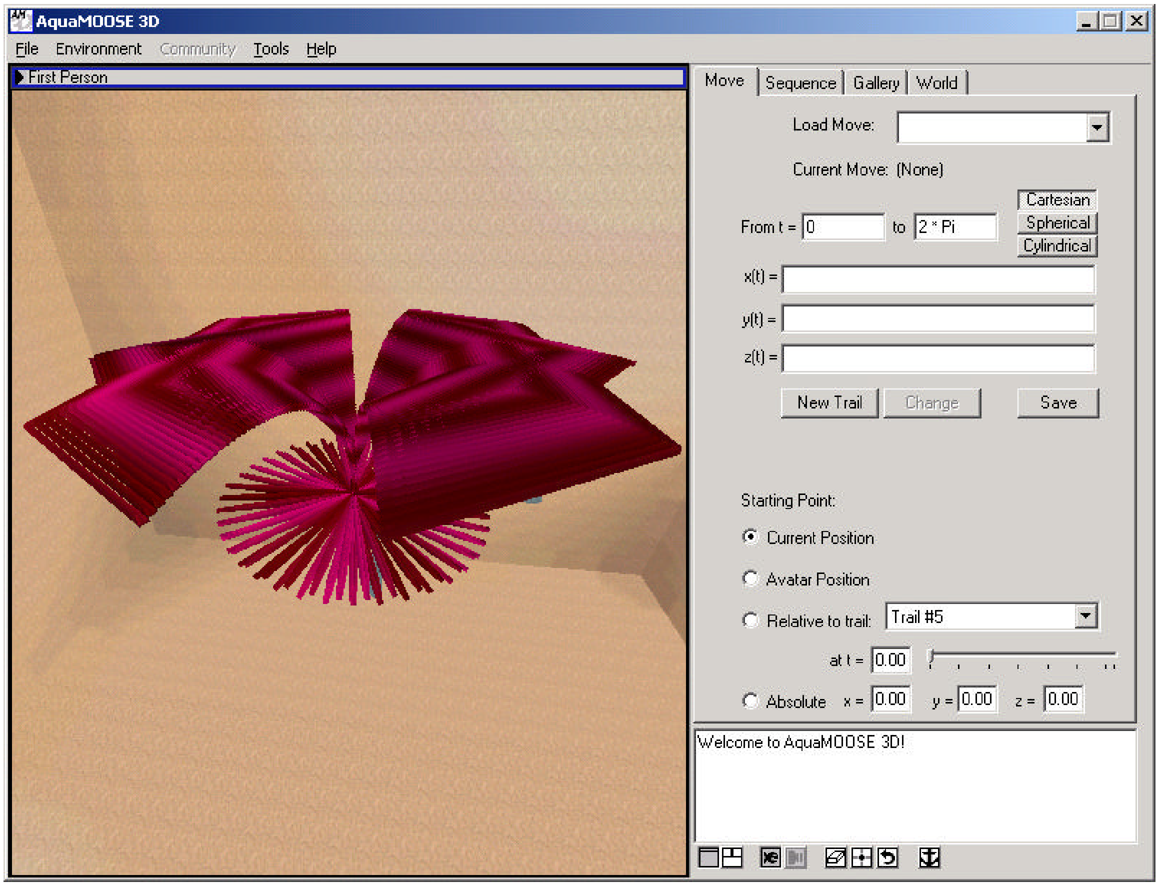


Figure 6.12: Cam's "Waterfountain"

6.1.4.3.7 Case Analysis

Cam spent the majority of the after-school program using simple math to create macro-scenes like his basketball court and his volleyball court. He used the same equations (straight lines and high-frequency sine waves) almost exclusively to create those scenes. Even then, though, he was learning how to use Cartesian axes to draw rectangular objects using math. Cam describes his experience creating the basketball court:

> First I created the [basketball] court thing… it was just figuring out the z and x coordinates, so it's simple… and like the nets and stuff are just like z and y and

> stuff… and the wall, I did ask for your help… and just put it together… just have to have a sense of direction and then put it together.

At the very end of the program, Cam branched out and began using curves to create an outdoor fountain scene. In a post-interview, he stated that he was not finished with several of his artifacts and would liked to have had more time to continue working on them. This transition from simple math to more complicated constructs demonstrates the potential of the AquaMOOSE system for promoting intellectual growth and engaged experimentation for some students.

In Cam's case, math was not the primary focus. His personal style was goal-oriented: he planned out his artwork and then created it using the most readily available math equations that would meet his needs. Cam understood the math and experimented with complex equations throughout the program, but he primarily concentrated on his goal for a finished product. The software appealed to Cam because it allowed him to easily create and present the artworks he desired. His goals focused primarily on representations of real-world objects that he came into contact with regularly, like the basketball court and volleyball court. Toward the end of the program, however, Cam began to explore how he could use math for even more interesting scenes than he initially envisioned. His fountain, even in the intermediate stage, is a beautiful and more abstract creation compared to the straight lines and walls of the other projects he completed. Cam's experience demonstrates how the AquaMOOSE system can support participants' evolving usage patterns.

6.1.4.4 Case Study #4 – Tong

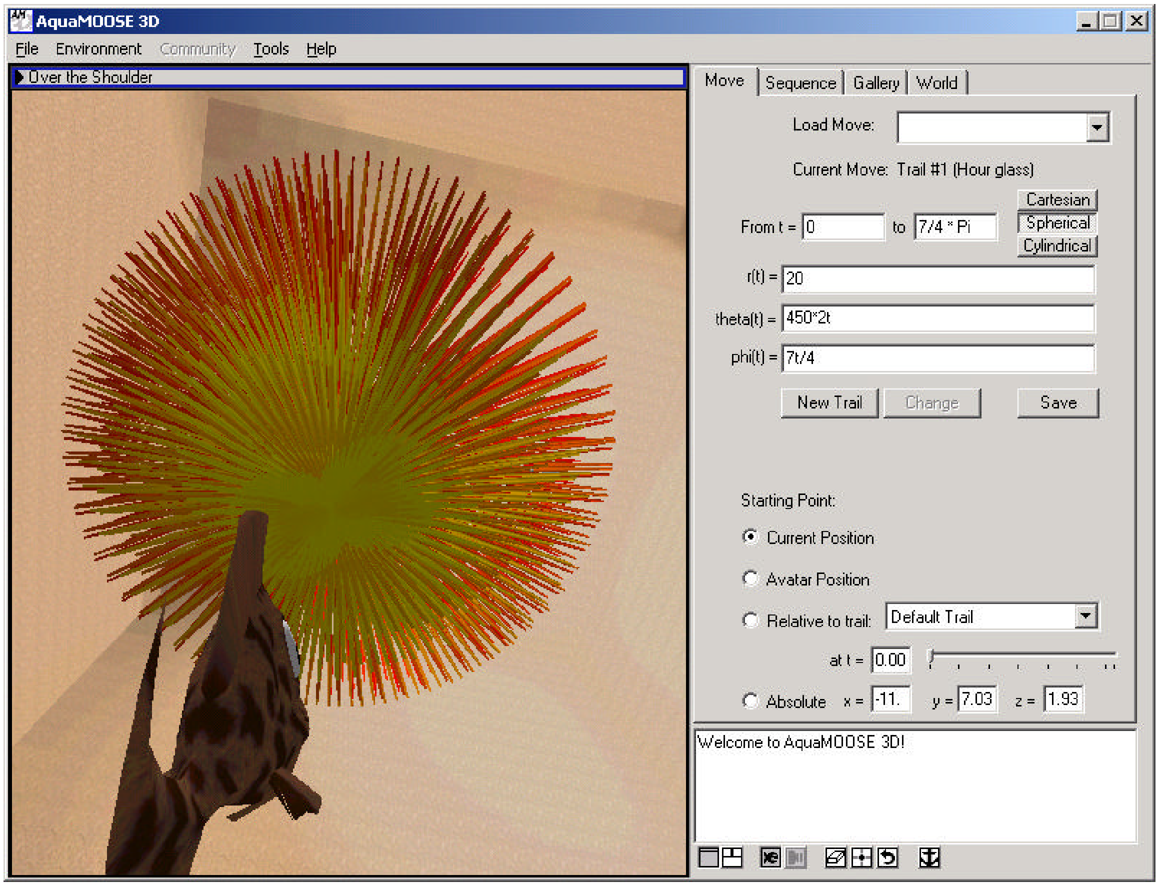


Figure 6.13: Tong's "Porcupineball"

Tong is an Asian male student in the 12th grade. Of the five students discussed here, Tong is the one who attended the fewest sessions of the program. He came to the first three sessions of the program, but did not attend the next four. He unexpectedly returned for the final session of the program, which is the main reason for his inclusion here. He is an older student who seems very confident in his abilities, and usually wears a black glove on one hand. He draws a lot, and considers himself to be both an "art person" and a "math person." When asked about his favorite subject in school, he said, "I like both math and art because math provides the basis of my analytical thinking and art provides the expression that I would like to express."

Tong focused not only on creating interesting artifacts, but also on presenting them in an artistic manner to the audience. He spent a lot of his time modifying colors and camera angles for his artifacts, rather than exploring different math equations. In his artifact called "Ring of Fire," it is clear that Tong has positioned both the fish avatar and the camera in specific ways to present the scene as a work of art (see Figure 6.14). None of the other students used the external camera to present artifacts in this manner.

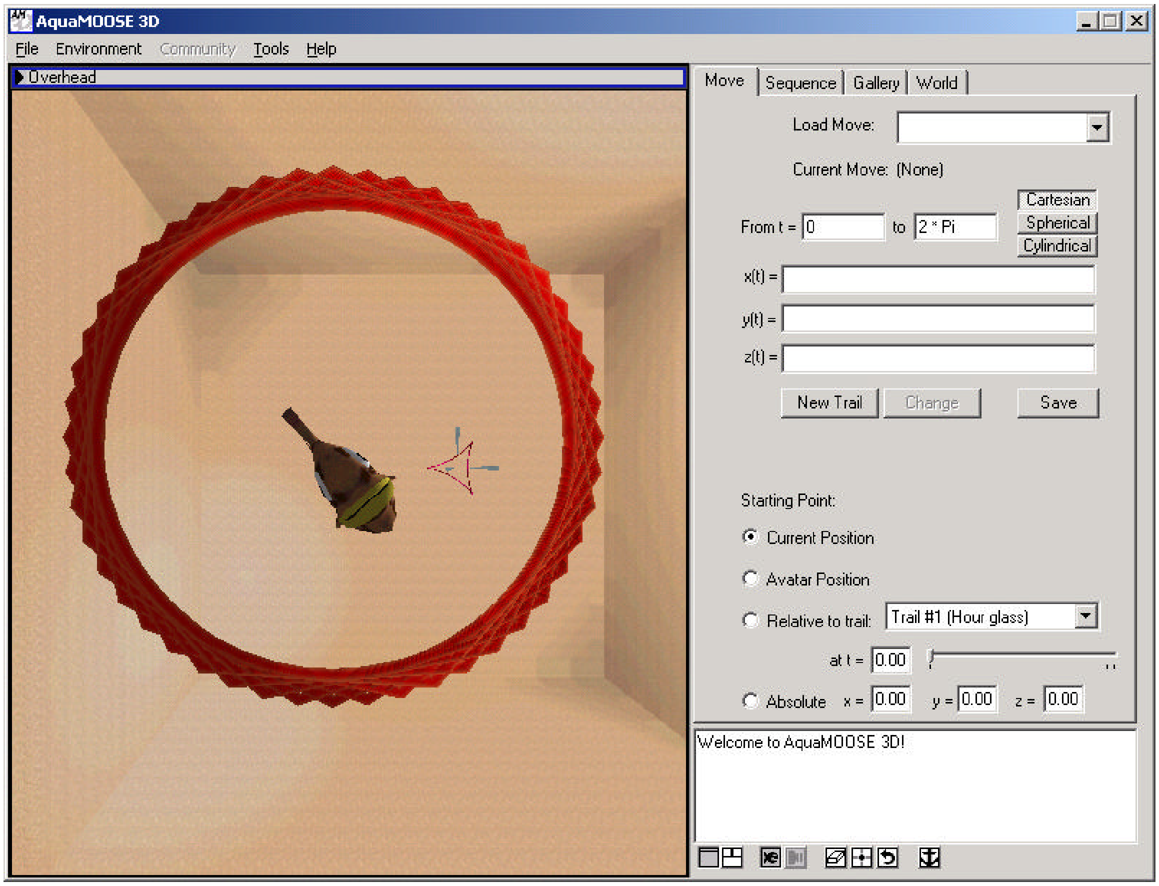


Figure 6.14: Tong's "Ring of Fire"

6.1.4.4.1 Session One

Tong came in for the first session of the program and began talking with Cam. The two of them are friends and worked closely with each other throughout the program. Tong was eager to try out the software, and constantly moved ahead to try out new things during the software introduction. Of all the students, Tong was the most comfortable with the technology. He immediately understood how to interact with the AquaMOOSE software, and promptly explored all of the different features available in the software.

Most of Tong's trails during the first session were based on sample trails. Once he found a sample trail he liked, he edited the equations a few times to make something a little different, made some changes to the trail colors and properties, and then moved on to a new project. In general, the amount of time he spent on any given trail was short.

6.1.4.4.2 Session Two

Throughout the program, Tong seemed more concerned about the trail colors and properties than the other participants. Tong says, "I don't exactly understand how all the math works, so when I try to do it, I try to look at the art, how it looks, and change it to how I like how it looks." In the second session, he created several variations of a sphere trail and spent time exploring different psychedelic effects using trail colors and properties (see Figure 6.15).

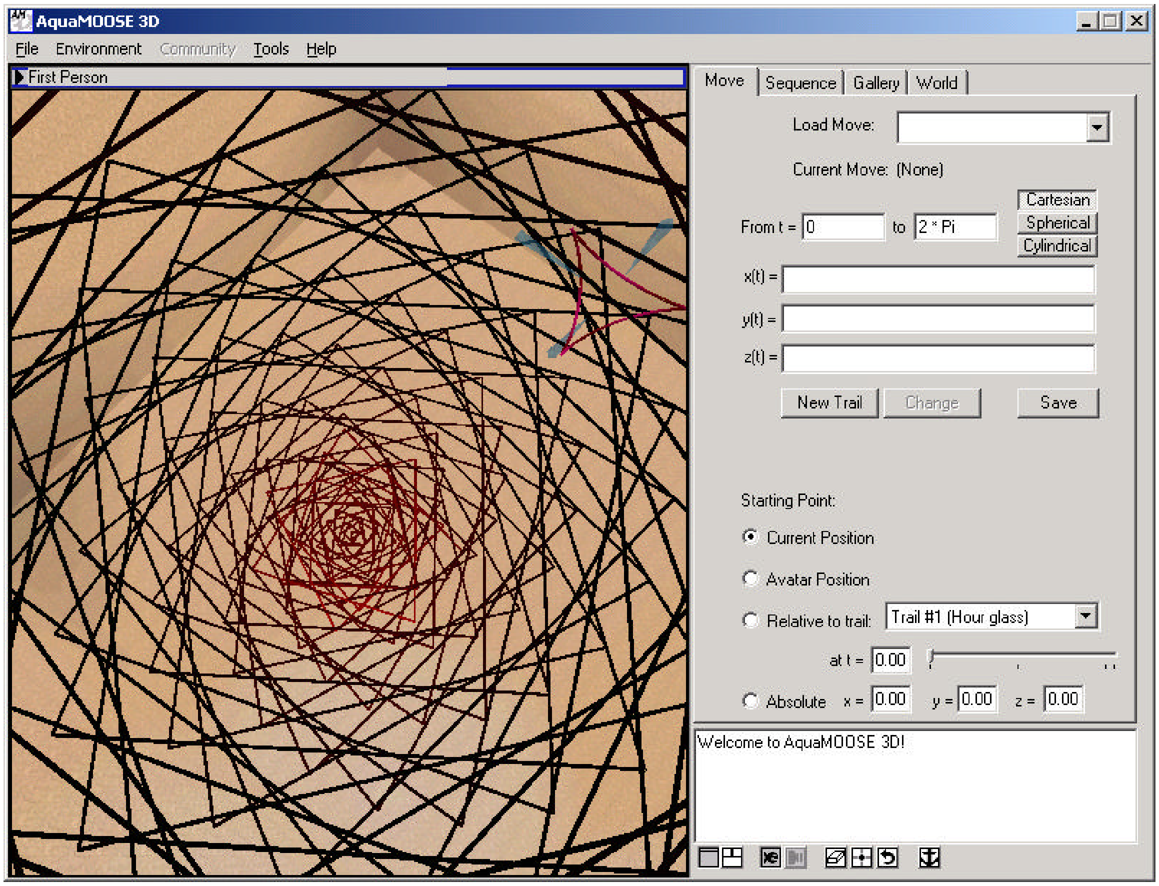


Figure 6.15: Tong's "Hypnotize"

As in the first session, Tong always seemed to be a step ahead of the researchers, exploring new trails and new aspects of the software before prompted to do so. His engagement was on a deeper level than the other participants. He understood the software and the mathematics involved better than the other students. In this session, Tong sat at a computer between Cam and another participant. Tong's presence between the other two students was clearly helpful.

The lecture topic for this session was a quick overview of polar coordinates and parametric equations. Tong seemed to be paying particularly good attention and possibly retained more from the lecture than the other participants. In his post-interview, Tong said he had encountered similar problems on his AP calculus exam and had used some of the methods discussed in this session's lecture to help him solve those problems.

6.1.4.4.3 Session Three

The third session of the program introduced the real-life artifact project, where participants were encouraged to pick a real-life artifact and try to represent it using the AquaMOOSE software. Like the other students, Tong explored some of the sample trails provided by the researchers to get ideas about his own project. The types of manipulations Tong did with the artifacts were very different from the other students, however. He took the "wicker basket" trail and performed several mathematical manipulations on it, including stretching it vertically, flattening it, and flipping it upside down. He then performed similar operations on other trails, including the "bulb flower" trail. Tong demonstrated an understanding of the underlying math concepts that was more developed and more accurate than the other participants.

Later in the session, Tong took the "cup on saucer" trail and began manipulating it in a similar manner to that described above. In the opinion of the researcher who created the original trail, Tong made the trail look even more like the teacup he had originally envisioned. Tong then proceeded, with some help from that researcher, to add a wisp of steam coming off the cup of tea he had created.

Tong received several phone calls during the session, which resulted in him leaving about 25 minutes before the end of the session. Before he left, the researchers asked him if he had chosen a real-life project to work on during the next session. He responded that he was just "playing around for now." Tong did not return to the program again until the final session five weeks later.

6.1.4.4.4 Session Eight

Tong's arrival at the eighth session was a surprise to the researchers. He seemed mostly interested in seeing what the other students had done while he was gone. Instead of opening his own folders of creations, he started by talking to Cam about his objects and then browsing the public folders of the other participants. Tong was impressed by the other students' artifacts, and was interested in the new software features that he had not used earlier, such as trail sequences and scenes.

As the final presentation session was about to begin, Tong quietly got up and left the room. I had hoped he would present some of his own creations, but he did not return. One of the teachers who knew Tong was participating in the program also asked about him and was disappointed that he did not show his artifacts during the presentation session.

6.1.4.4.5 Case Analysis

Tong began his participation by creating small "throw-away" projects. He worked furiously to create numerous artifacts that he quickly saved and then abandoned. In the first few sessions, Tong was more interested in exploring the capabilities of the software than in creating something specific. He seemed to enjoy trying out different equations, and had a better prediction model of the 3D outcomes than the other participants.

The primary motivating factor for Tong seemed to be the social interaction within the group, specifically with Cam. He spent most of the sessions talking closely with Cam, both watching Cam create and sharing his own creations with Cam. Their conversations were very quiet and mostly unintelligible to the researchers in the room.

About halfway through the program, Tong stopped coming to the sessions. The researchers assumed he had dropped out and would not be returning. However, at the final session, Tong returned and was excited to see what the other participants had created. When asked about his absence, he responded, "I had 3 AP exams. I was ok on the first two… but the third one… AP

Physics...” Tong briefly looked back through his own objects, but spent most of the final session browsing other students’ creations and watching Cam show off his work. Tong left at the end of the final program session and did not participate in the public presentations.

In Tong’s case, the social setting is a motivating factor. The after-school program and the AquaMOOSE software are designed to provide a clear audience and easy methods for sharing creations. Tong was most excited about this social aspect of the program, and even came back after missing several sessions just to see what the other participants had created. Designing socio-technical systems that support interaction among peers helps engage students like Tong. Tong’s personal style is highly mathematical. He created and refined his objects very quickly, then saved them and moved on to a new project. His artifacts are visually appealing, but usually involve simple mathematics. He also made use of the same equations in different coordinate spaces to create multiple artifacts.

6.1.4.5 Case Study #5 – Maria

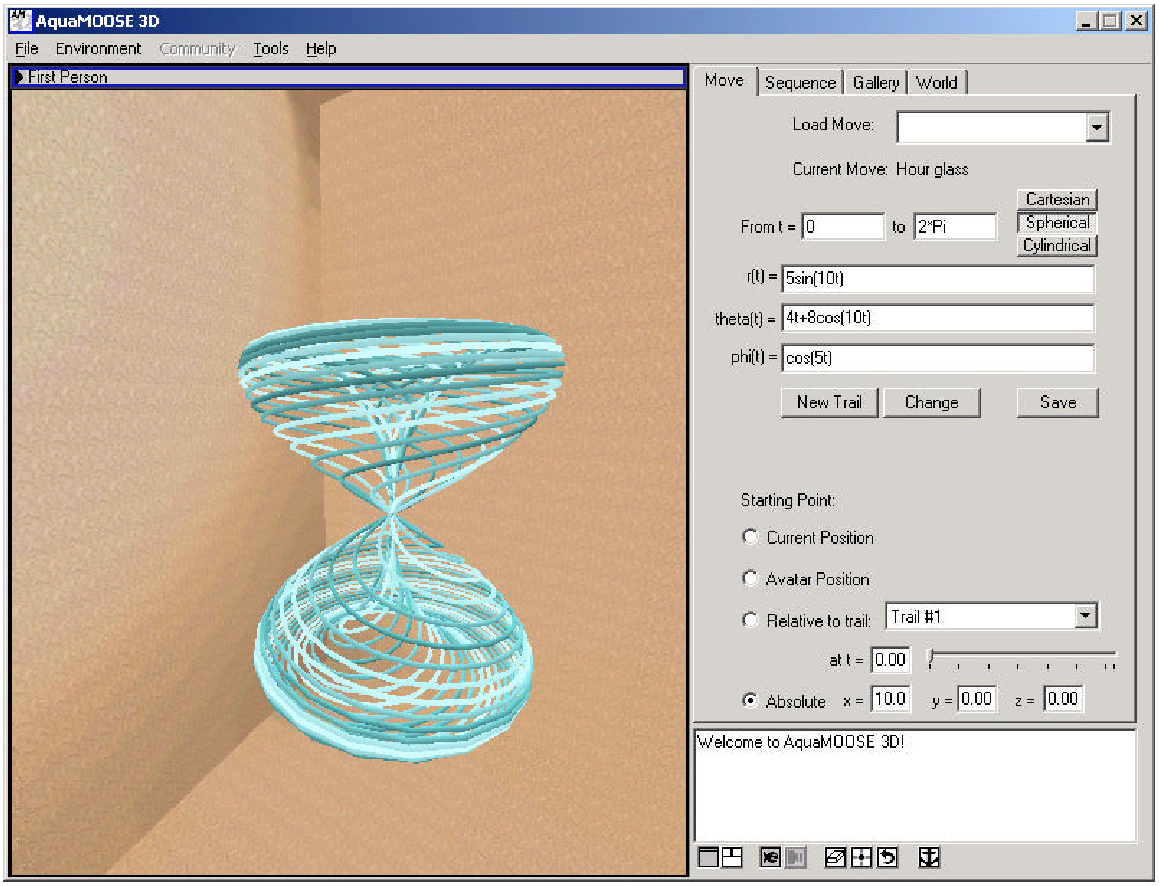


Figure 6.16: Maria’s “Hour glass”

Maria is a Hispanic female student in the 11th grade. Maria is primarily a math student. She also loves to draw, but does not feel that she does so very well. In almost every session, Maria was the last student to arrive, sometimes showing up half an hour or more after the session started. She was the only student who attended every session, however. Her process for creating artifacts involved more deliberate manipulation and iteration of the mathematical equations. Her goal was to create something recognizable, and she was often disappointed when her equations generated an abstract artifact instead. On several occasions when she created these visually appealing abstract objects, her response to a researcher’s compliment would be “yeah, but I don’t know what it is and I’m not sure what to call it.”

For Maria, the social aspect of the program seemed to be less appealing than it was for the other participants. She wanted to have people in the program, and thought the program would have been fun with more people, but she also said, “Sometimes when I was doing things and I wasn’t really sure what I was doing, I didn’t really like people being around me, since I thought… what if I do something and they think it’s weird… I don’t want them to be there watching me.”

6.1.4.5.1 Session One

Maria arrived more than an hour late for the first session, which meant she had only a few minutes to use the software after completing her surveys. She began by trying out one of the sample moves, called “slow rollercoaster.” This move takes 100 seconds to complete and is designed to show how moving through the equations can be as entertaining as the end product. As the fish moves through these particular equations, it feels somewhat like riding a roller coaster. Maria watched as the move started. About 30 seconds later, I informed Maria that she could interrupt the move and try something else if she wanted, but she declined and continued to watch the entire 100 seconds of the move. She went on to explore some of the other sample moves. Like most of the other students, Maria was intrigued by her first use of the software, and was not in a hurry to leave when the session ended a few minutes later.

6.1.4.5.2 Session Two

Maria arrived during the presentation of polar coordinates and parametric equations at the beginning of the second session. After the topic presentation, she began working on the Sphere challenge. Since she had only a few minutes to use the software in the first session, Maria spent a lot of time familiarizing herself with its features during the second session. She seemed less comfortable with computers in general, which did not help her catch up to the other students.

Maria was able to explore several variations of spherical trails using spherical polar coordinates, but seemed less enthusiastic about the creative process. Maria was focused on completing the challenge and was frustrated by difficulties navigating and viewing trails in the 3D environment.

6.1.4.5.3 Session Three

Maria began the third session by loading up a trail created by a researcher called “wicker basket.” She started modifying the trail randomly, changing multiple equations at once and generating some interesting effects. Unlike the other students, however, Maria spent a lot of time staring at the trail trying to understand how the visual trail representation and the math equations related to each other. Maria asked for help numerous times, usually about software features or problems that she was having trouble understanding.

After exploring variations of the wicker basket for quite some time, Maria ended up with an abstract creation that looked like two pinwheels going in opposite directions with some depth variability thrown in for good measure. She liked the way the trail looked, but was disappointed that it did not remind her of anything real. After receiving compliments on the trail from the researchers, Maria asked for help in naming the trail. One of the researchers suggested that it looked like a dandelion, so Maria chose that as the name for her trail (see Figure 3.19). Maria left the third session early.

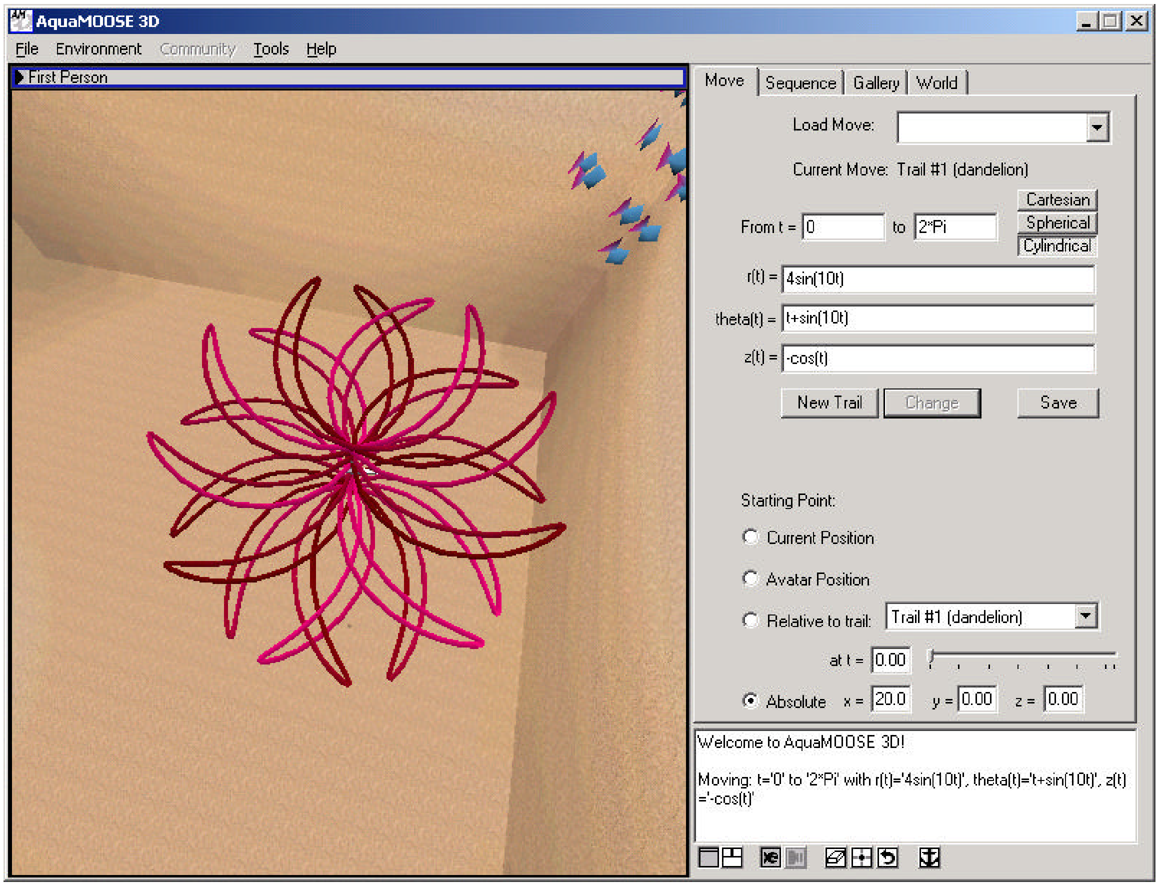


Figure 6.17: Maria's "Dandelion"

6.1.4.5.4 Session Four

Maria was one of only two students at the fourth session, and was shy about getting so much attention from the researchers. She began the session by loading and manipulating some of the sample trails provided by the researchers. Maria changed the equations seemingly at random and ended up with numerous abstract creations. Many of them were visually interesting, prompting more discussions between Maria and the researchers about what to name each artifact. Despite being disappointed that she was unable to create "real" objects, Maria saved all of her abstract trails and acknowledged that they were visually appealing. When asked about her favorite part of the AquaMOOSE after-school program, she responded, “When I would try out different equations to make stuff, and it wasn’t exactly what I wanted, but it was cool anyway.”

Maria seemed to understand the math involved in the AquaMOOSE software better than some of the other students. However, she usually did not have any artistic goals driving her exploration. At one point, she tried to add a head under a “hat” trail, but quickly gave up and went back to random manipulation of single trails. That was the only time Maria tried to use multiple trails to create a scene.

6.1.4.5.5 Session Five

Maria spent the fifth session preparing for the informal critique presentations. She decided she was going to present her “hourglass” trail (see Figure 6.16 above), since it was her favorite and one of her only trails that “looked like something.” Like the other students, Maria was shy about presenting her artifact to the rest of the group. She was the only one who filled out an artifact description document before the presentation, though, which helped her talk about the artifact in greater detail.

Maria received positive feedback about her hourglass, as well as some suggestions about how to add to it and improve it. One researcher suggested that she could make a trail sequence to show the hourglass flipping over. I suggested that she could use trail properties to color the sand inside the hourglass a different color than the exterior. We spent some time after the presentations trying to help Maria achieve the sand coloring effect, but were unable to isolate the “sand” parts of the trail.

6.1.4.5.6 Session Six

Maria spent the sixth session working on the Butterfly challenge. She made amazing progress on the challenge and ended up with some impressive artifacts. She created her cocoon very quickly, and then moved on to making her caterpillar. One thing that made Maria's work on the challenge go smoother was the numerous abstract trails she had saved during previous sessions. She used her own trail folders as a library of starting points. For each of the three components of the Butterfly challenge, Maria began by looking through her folder and finding a move that appeared most similar to what she was trying to create. She explains this process of reuse:

> I would see which type of equations I could use to get certain shapes, and then when I wanted to do something different, I would try to remember… what equations did I use to make this… and then I would use that. And then I would change the coefficients to make it longer, shorter, or wider.

When she was working on her butterfly, the most complicated of the three trails, Maria decided to replace all sine and cosine functions in her equations with natural log functions. This resulted in many undefined points that defaulted to a 0 value, creating "spikes" in her trails that reached out to the origin. Maria enjoyed this effect, and briefly played around with making trails "explode" in this fashion. She created a trail sequence of a "party favor" artifact exploding, but did not save the sequence itself.

Maria also spent time generating interesting animation effects on her trails with the Trail Properties features of the software. She changed pulsing animation properties to give her caterpillar and cocoon a more life-like appearance. Despite creating impressive versions of all three components to the Butterfly challenge, Maria never completed the challenge by adding them to a trail sequence (see Figure 6.18).

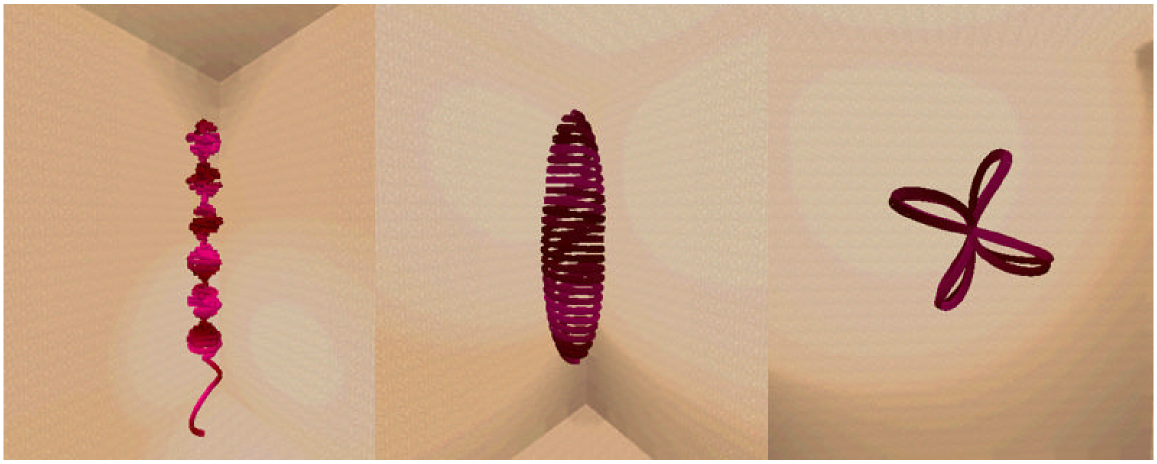


Figure 6.18: Maria’s Butterfly Sequence (“Caterpillar,” “Cocoon,” and “Butterfly”)

6.1.4.5.7 Session Seven

During the seventh session, Maria spent a lot of time reorganizing all of her previous creations. She created folders to hold her various artifacts, and renamed and moved around many of her trails. She also completed artifact description documents for several of her creations. Maria was the only participant who actually used the artifact description documents with any regularity.

After organizing her folders, Maria went back to her butterfly sequence components from the previous session. She created an entirely new caterpillar trail to replace the one she made during the sixth session. Then she created a trail sequence with all of the components, which she had not done during the previous session. She seemed comfortable with the trail sequence interface, and enjoyed playing around with different effects for her butterfly sequence.

Maria explored some of the other sample scenes towards the end of the session, including a hot air balloon scene created by one of the researchers. She didn’t edit the scene at all, but instead just moved around and explored the visual aspects of the scene. She left the session early.

6.1.4.5.8 Session Eight

Like the other students, Maria spent the beginning of the eighth session preparing for her final presentation. After she had her presentation lined up, she left the room to go wait for her family to arrive. Her mother, brother, and sister all attended the final presentation session.

When the presentations began, Maria was asked to go first but shyly declined and asked to go later. She ended up presenting last instead. She was shy and insecure at the beginning of her presentation, discounting any of her artifacts that didn't look like real objects. She presented her "hourglass" trail first, stating that she was proud of it because it was "the first thing [she] made that looked like something." Next she showed her "funnel" trail, which she was proud of because it was the second thing she made "that looked like something" (see Figure 6.19).

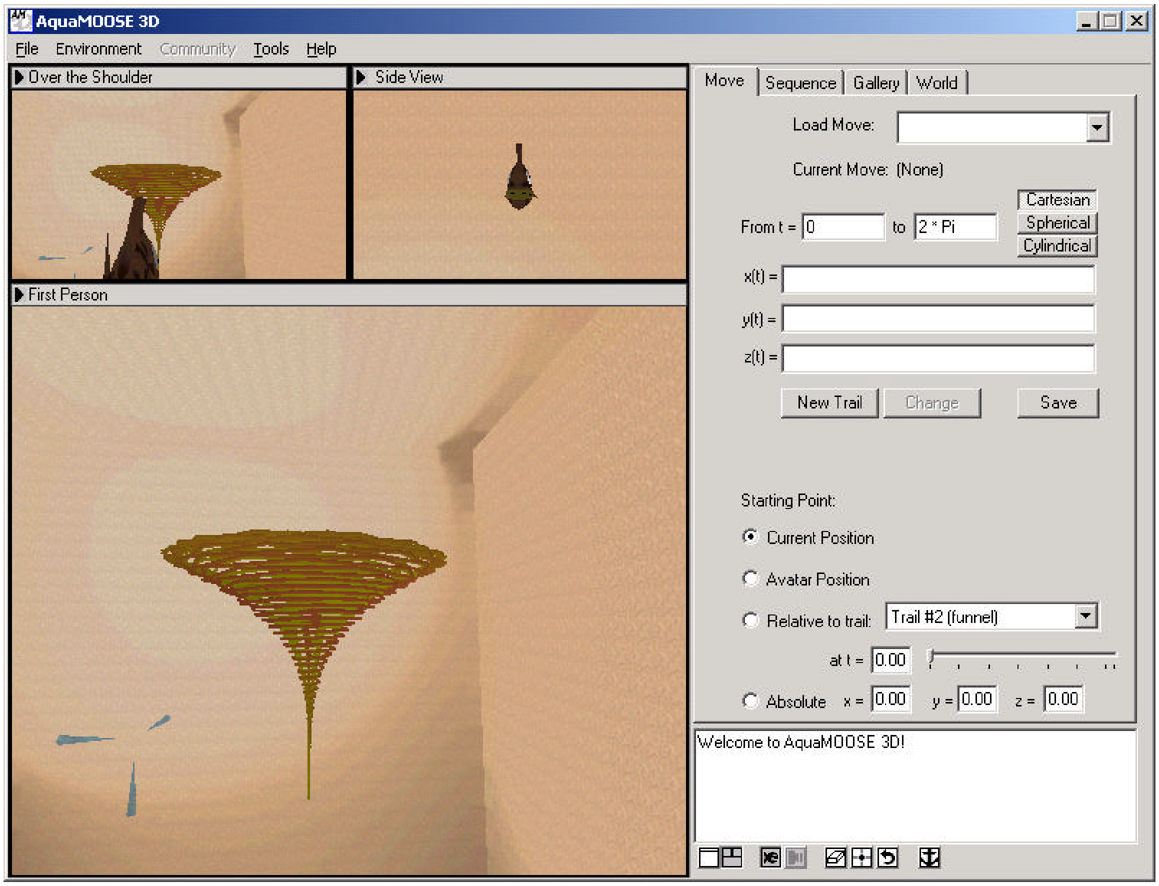


Figure 6.19: Maria's "Funnel"

After showing one more creation, Maria seemed to be finished with her presentation. However, some of the teachers present noticed that Maria had numerous other artifacts in her folder and asked to see them. The audience was impressed with all of Maria's abstract creations, which came as a surprise to Maria. When she realized that people were interested in her abstract creations, she became much more enthusiastic and ended up showing and discussing many of them.

6.1.4.5.9 Case Analysis

Throughout the after-school program, Maria had trouble coming up with artistic goals for her exploration. She focused on completing the challenges that were given to her, but did not explore many trails beyond that scope. She understood the math involved better than most of the other students, but ended up doing random manipulations of the equations that almost always resulted in abstract artifacts. Maria was less confident in the validity of abstract creations, despite positive reinforcement from the researchers on several occasions.

During the final presentation, Maria experienced a transformative event. She finally realized that people were just as impressed with her abstract creations, and the quantity of them she had created, as they were with her representational artifacts. She became enthusiastic about showing off those abstract trails and was happy to talk about how she created them. As with Cam's experience, the AquaMOOSE socio-technical system facilitated and supported Maria's changing goals and perspectives.

6.1.5 Discussion

As we predicted in our fourth hypothesis above, each of the five students presented in this section had different experiences while participating in the THS after-school program. Each student had a different initial mindset at the beginning of the program that resulted in varied strategies for artifact creation. The general approach that the students took is shown in Figure 6.20.

Experiment
Form aesthetic goal
Refine math equations
Receive feedback
Complete artifact

Figure 6.20: Typical creation process in the AquaMOOSE system

The experimentation and goal-formation phases of the process, however, were different for each student. The Challenges provided by the researchers (see Appendices A.2 through A.5) provided one starting point for some students. Other students, like Cam and Tong, used the experimentation phase to explore different mathematical capabilities within the system instead of focusing on the Challenges we provided. Sarah used the Challenges as a stepping-stone to guide her through the goal formation phase, often branching off from the goals of the Challenges to create artifacts that were more personally relevant to her.

The feedback phase of the process also proved to be critical for the students in our after-school program. Throughout the program, Maria was concerned that the artifacts she created did not look like recognizable real-world objects. Positive encouragement from the researchers helped Maria continue her exploration of abstract shapes. In the final presentation, Maria's hesitation about abstract artifacts was again dispelled by an even broader audience. The feedback phase throughout the AquaMOOSE program helped Maria come to the conclusion that abstract art is as valid as representational art. The anticipation of the final presentation was also influential for Cam. The goal of presenting his portfolio to others drove him to recognize a new type of artifact than what he had created during the rest of the after-school program. Instead of focusing entirely on rectangular objects, he invested time into completing an artifact based on a failed experiment that resulted in a flowing, curved shape.

Before the after-school program, we also hypothesized that students would be able to leverage the synergy between math and art designed into the AquaMOOSE system to improve their level of interest in one or both of those areas. While the results from the five students described above show the potential of the system for engaging students in new math learning experiences, our small sample of participants was not sufficient to provide insights into how prior interests affect the success of the AquaMOOSE intervention. Further research is needed to answer those research questions and to better understand how prior interests can be leveraged to increase students' engagement with new learning activities.

The AquaMOOSE after-school program provided students with a supportive context for exploring new kinds of math. The students who participated created numerous visually appealing artifacts that exhibited their personal styles. The combination of structure and flexibility we incorporated into this instantiation of the AquaMOOSE system was able to accommodate a variety of different learning approaches. By carefully designing the social as well as the technical aspects of the system, we were able to provide an opportunity for these students to experience a new type of math learning activity.

6.2 Extended Importance of Audience

The final session of the THS study included a public presentation of the students' portfolios to an audience of friends, teachers, and family. This presentation proved to be a critical component of the program's success for several participants. Not only did the presentation drive the students to complete their portfolios and describe their artifacts, but it also allowed them to reflect on their learning activities and to consider different possibilities for future creations.

Two students in particular had transformative experiences during the final presentation. One student spent the entire study creating rectangular scenes built mostly out of straight lines. He was not interested in exploring curves or other more complex mathematical equations. He used straight lines to create a basketball court and a volleyball court. Just before the final presentation, however, he tried to add a new component to one of his other creations and mistakenly ended up with an interesting trail that resembled half of a water fountain. He was pleased with the errant creation and decided to present it in addition to his other artifacts. The audience liked the water fountain object. Through his presentation of this artifact, he began to realize the diversity of creations he could make using the software. Another student made numerous abstract creations throughout the program, but always disregarded them since they did not resemble anything recognizable. In the final presentation session, a teacher noticed that the student had a lot of artifacts she was not presenting and asked her what they were. She reluctantly shared a couple of the creations with the audience, and found that people were as interested in those creations as they were in her more representational artifacts. Once she realized that people enjoyed seeing her abstract artworks, she became more enthusiastic and continued presenting several more of them.

6.3 Scenes as a Connection to Art

The most influential addition to the THS release was the ability to save everything in the 3D space as one scene. This reinforced the connections between math and art in a very concrete and recognizable way. One student used scenes much like an artist would paint or a photographer would take a picture. He created a moderately interesting mathematical trail in the space. Then he would color the trail and animate it. Finally, he would move the cameras around until he found the exact view of the trail he wanted to share with others. From any other perspective, the math trail looked mediocre at best. But with the coloring and camera positions he saved, the student was able to present an interesting visual image. Other students also used scenes to save color, animation, and camera position information for their artworks. Scenes played a crucial role in motivating and engaging the study participants by connecting the mathematical and artistic aspects of the AquaMOOSE system.

6.4 Time Required for Substantial Benefits

The semi-structured design of the THS study proved to be more effective than the free-time use of the GHP study or the classroom use of the BHS study. However, even with an after-school program that lasted 8 weeks, it was clear that the students were just beginning to understand and utilize the AquaMOOSE system. Several students experienced transformative events during the final presentation session of the program that would have helped them continue to grow and expand their understanding of the AquaMOOSE environment. Other participants seemed reluctant for the program to end, and wished they had more time to create more mathematical artworks. One student even asked at the final session what was going to be covered during the next week. She failed to realize that the program was over, and was interested in continuing her exploration beyond the limits of the research study. From all of the deployment studies we completed, we have seen that it takes a substantial amount of time for people to become comfortable with a new technology and to make use of it. Constructionist learning environments such as AquaMOOSE seem more effective when they can be used for a longer period of time.

6.5 Structure of the Social Context

The GHP and BHS studies clearly showed that we needed a new model for the social aspects of the AquaMOOSE system. The social context around the system plays a critical role in motivating students and providing them with an audience for feedback and praise. The lack of structure in the GHP study resulted in few students becoming engaged with the system. The traditional classroom structure in the BHS study did not give students enough time or motivation for understanding the AquaMOOSE software and its benefits.

In the THS study, we designed an after-school program to balance the freedom of the GHP study with the structure of the BHS study. Participants in the study were required to apply to participate in the after-school program. This provided the students with a sense of commitment to the program. Once students were in the program, they were given the freedom to explore and create whatever they wanted using the AquaMOOSE software. We provided challenges at most of the sessions, though, to give the students some starting points and some possibly interesting ideas to pursue. Some students ignored the challenges and created completely different artifacts. Other students completed the challenges exactly as they were presented and went no further. Still other students began working on the challenges, but decided to switch to more personally meaningful goals based on an intermediate artifact from the challenge. This combination of freedom and support allowed students with a variety of backgrounds and learning goals to benefit from the AquaMOOSE system.

CHAPTER VII

DISCUSSION AND CONCLUSIONS

The past seven years have given us the opportunity to explore and evaluate the potential of 3D graphical virtual worlds for learning. Throughout that time, we have encountered numerous design issues that influenced the outcome of the AquaMOOSE project. In this chapter, I present the lessons we have taken from dealing with those issues and apply those lessons to our research agenda. Our hope is that these insights may help other researchers who are contemplating similar issues in their own research.

This chapter presents the research findings related to our two research questions. The findings for the first question deal with supporting a constructionist learning environment for complex content material, and include the following sections:

- Balancing Structure and Freedom
- Engaging Students through Art
- Supporting Multiple Paths to Goal Formation
- Emphasizing Audience
- Designing for Sufficient Time on Task

The second set of findings address the tradeoffs of using 3D technology to support this type of constructionist learning activity, and include the following sections:

- Visualizing Complex Math
- Personal Connections to Art
- Curriculum Goals Versus Technological Capabilities

- Scalability

The chapter concludes with some final remarks about the process of developing and evaluating a constructionist learning environment for complex content.

7.1 Research Findings

The AquaMOOSE project was created to explore how new technology could be used to build a compelling constructionist learning environment. Two questions form the core of the AquaMOOSE research agenda:

- When the content that we want learners to learn using a constructionist software system is complex and very technical, what is needed in the supporting socio-technical system so as to engage the learners adequately?
- What are the tradeoffs in using 3D technology to support complex math learning?

In this section, implications based on evidence from the design and evaluation of the AquaMOOSE socio-technical system are presented.

7.1.1 Supporting Constructionist Learning of Complex Content

Throughout the AquaMOOSE project, we have explored using different aspects of our socio-technical system to support the constructionist learning process. We have used the AquaMOOSE system in different learning contexts with varying levels of structure and freedom and have designed specific features and activities to engage students in artistic activities. We have used feedback from formative evaluations to further refine our socio-technical system. By doing so, we have been able to better understand how a constructionist learning environment for complex content can be used to engage learners with a variety of prior styles, goals, and abilities.

7.1.1.1 Balancing Structure and Freedom

In our first user trials with the AquaMOOSE software, we noted that the interaction between the participants played an important role in their experience with our system. Students created artifacts at their own pace and shared their creations with each other while talking about how they created them and what they planned to create next. This observation led us to create a social context that followed a more radical view of the constructionist philosophy – simply give students an interesting tool and they will do interesting things and become engaged with the material they are learning. However, when we tried this method during our first large-scale user trial at the Georgia Governor's Honors Program, we had only a few students who used the system with any regularity (see Chapter IV). Not all free-time use is equivalent, and we found that specific issues related to free-time use at the GHP certainly played a role in our results.

Free-time use allows participants to explore a diverse set of activities, but our experience has shown that more structure is needed to guide students through new learning activities. Other tools may work better with free-time use contexts, but our early studies indicated that the AquaMOOSE system needed to provide more guidance for the students. Whether that structure is built into the tool or provided by the social context surrounding the tool, it must help students understand both how to engage in the activities that are available and why those activities are relevant to the students. Competing activities often pose additional difficulties for free-time use. In our GHP study, the participants could sit in the computer lab and explore the AquaMOOSE tool, or they could choose an entirely different activity like going outside to socialize with other students. Even in prototypical constructionist learning environments (Falbel, 1989), implicit social structures indicate to the students that they are at a school and their task is to learn. Our research has indicated that while the idea of students engaging in personally meaningful learning activities voluntarily is appealing, some level of structure is necessary to help support the students' learning process.

The second deployment study we conducted was in a high school where we designed a curriculum around the AquaMOOSE system to teach students about polar coordinate space (see Chapter V). Our curriculum was based on the standard curriculum guide used by the high school and aimed to achieve the same learning outcomes. That social context design was the polar opposite of the first study we conducted where students used the AquaMOOSE system in their free time. The AquaMOOSE curriculum designed for the BHS study attempted to engage all of the students in a high school pre-calculus class in the same learning process. We provided specific activities and examples that the students could explore to better understand polar coordinate space, 3D parametric equations, and trigonometry. At the end of the study, we gave the students content tests. Three months after the study, we administered a retention survey that asked general questions about polar coordinate space and parametric equations. The difference between the scores on the content test in the comparison class and the AquaMOOSE class were not statistically significant, and neither class remembered anything about polar coordinate space or parametric equations when asked about them on the retention survey.

We believe there were several reasons for the results of the second AquaMOOSE evaluation, which are discussed in more detail in Chapter V. One important influence on those results, however, was the mismatch between the structured classroom curriculum we used and the open-ended constructionist philosophy we used to design the AquaMOOSE system. The students in our second study did not have the freedom to explore the capabilities of the AquaMOOSE software or to engage in learning activities that they found personally relevant. Constructionist learning environments are fundamentally opposed to the type of rigid structure found in many school classrooms today.

Free-time use did not produce the engagement we anticipated, and the rigid structure of school curriculum did not allow students to explore the system to find personally meaningful activities. As a third option in the spectrum of social contexts, we designed our final study as a semi-structured after-school program for high school students (see Chapter VI). The participants in the THS study chose to participate in the program because of personal interests. They were given specific challenges that demonstrated various features in the AquaMOOSE software, but were not required to complete those challenges. The only goal we provided for the participants was to create a portfolio of mathematical artworks that they could share with friends and family during a public exhibition.

This semi-structured context for the AquaMOOSE tool gave participants the chance to explore unique and sometimes unexpected learning activities. One student focused on creating representational artifacts using primarily straight lines and learned about 3D Cartesian coordinates in the process. Another student developed a large set of abstract artifacts and then used them to build more complex creations. A third student worked diligently to solve the challenges provided by the researchers during the study, but ended up branching off from the goals of those challenges several times to create other artifacts that were more appealing to her. While not the only solution, the diversity of approaches and learning styles demonstrated by the students during our after-school program indicates that this type of constructionist learning environment is better suited to a semi-structured social context where some structure is provided to guide participants through the system but the ability to explore and discover personally relevant activities is also supported and encouraged.

7.1.1.2 Engaging Students through Art

In our first major evaluation, we saw how art could engage students in learning about complex math in the AquaMOOSE system. Mark's experience with AquaMOOSE at the Governor's Honors Program demonstrates how constructionist environments can support different creative activities that allow students to explore new ideas and concepts (see Section 4.1.5). Mark described the things he created in artistic terms, such as "barbed wire" effects and "tunnels." This language represents a connection Mark had formed between the mathematical activity in the AquaMOOSE system and the artistic goals he sought to achieve. Similarly, all of the participants in the final evaluation of the AquaMOOSE system were engaged by the artistic creation process. Whether they were attempting to fulfill representational goals, like Maria (see Section 6.1.4.5), or seeking particular artistic effects like Tong (see Section 6.1.4.4), each student was able to use the AquaMOOSE system to create personally meaningful mathematical artworks.

In our research, we have begun trying to understand how to engage students with different backgrounds in new learning activities. Our initial inquiries into why certain students become engaged while others do not have yielded some research questions that need further exploration. Characteristics such as visual and spatial ability, prior video game experience, and artistic ability seem to play roles in the success of the AquaMOOSE environment, but the exact nature of that role is still an open question for future research.

Though not all students become engaged with the mathematical components of the AquaMOOSE system through artistic creation, those who have demonstrate the positive impacts that are possible when using such synergistic connections. Our exploration of the connection between math and art in the AquaMOOSE system has shown that it is engaging for some learners, and suggests that other types of synergistic connections could be leveraged to engage students in different constructionist learning activities.

7.1.1.3 Supporting Multiple Paths to Goal Formation

In the final formal evaluation of the AquaMOOSE system at THS, the five participants demonstrated different methods of forming and reaching personally meaningful goals. Cam came into the after-school program with specific goals in mind, and was able to achieve those goals using the AquaMOOSE software. He wanted to create a basketball court and a volleyball court. Maria based most of her exploration on the Challenges we provided. She worked diligently on each Challenge, and was often the only student to complete them. Sarah began her exploration by working on the Challenges we provided, but often changed her goals due to intermediate results from those Challenges. For example, in working on the Butterfly Challenge (see Appendix A.5), Sarah thought that her intermediate cocoon trail looked more like a grape than a cocoon. She decided to abandon the Challenge goal and instead to create a bunch of grapes (see Figure 6.5).

For all of the students, once goals were formed, those goals often led to the creation of new goals. Initiating the goal formation process is key to getting students to engage in creating personally meaningful artifacts. Much like Sarah, who branched off to work on her bunch of grapes instead of the Butterfly Challenge, Cam realized an alternative goal while working on his volleyball court. During the process of adding more features to his court, Cam came up with a trail that was interesting. Cam then chose to use that trail, after some encouragement from the researchers, to create an entirely new scene that resembled a water fountain.

One important step for supporting this type of goal formation activity is to allow the students to experiment freely with the capabilities of the constructionist learning environment. This process is similar to the "messing about" activity described in the Learning by Design™ project (Kolodner *et al.*, 2003). Supporting such diverse paths to goal formation allows students to take control of their learning experience. The AquaMOOSE system, in its final instantiation, has demonstrated that a combination of flexibility and guidance can help students with different learning dispositions become engaged in the constructionist learning process.

7.1.1.4 Emphasizing Audience

Audience plays a critical role in the constructionist philosophy of learning. After becoming invested in a personally meaningful project, sharing the results of that project with other people gives the learner a chance to reflect on the concepts he or she learned in completing the project as well as to receive positive feedback about his or her creation. The audience can be present in the same physical space as the learner or distributed throughout the world with communication facilitated by the Internet. Whether the audience is physically present, distributed throughout virtual space, or even imaginary, learners must have the concept of an audience as an integral part of their conceptual model for the activity in order to provide the best opportunity for reflection and encouragement.

In the AquaMOOSE software, users connect to a server through the Internet. Each user has a private folder and a public folder where they can save mathematical artworks created in the AquaMOOSE environment. All users are displayed in a list with their public folders accessible, so that when someone shares an artifact, it is clear that all of the listed users will be able to see the artifact. This system of sharing artifacts was the primary form of audience until the final after-school program study. In our earlier studies, participants seemed to enjoy sharing their experiences and creations face to face with other participants in the same room. In the after-school program, we made sure we incorporated face-to-face communication into our study design. First, we encouraged students to take advantage of being in the same room as the researchers and other participants. In addition, we asked the participants to present their portfolios of mathematical artworks to an audience of friends and family during a public exhibition session at the end of the program. That exhibition session proved to be a critical component for the success of our after-school program (see Section 6.2). Participants grew to better understand their creations as well as the other possibilities that the AquaMOOSE software presented by reflecting on their experiences and sharing their artifacts with the audience.

7.1.1.5 Designing for Sufficient Time on Task

Constructionist learning environments depend on their participants to select personally meaningful activities. The process of selecting those activities is complicated and requires more time than we originally anticipated. First participants must learn how to use the software tool.

Then they must recognize or be guided through the recognition of the variety of activities and possibilities available in the software. Only after they understand the possibilities and have a mastery of the software tool can users begin to engage in personally meaningful constructionist activities within the environment.

In our study of students using the AquaMOOSE system during the Georgia Governor's Honors Program, we anticipated that there would be ample time for students to engage in personally meaningful projects. However, the free-time use context of that study combined with competing activities to limit the exposure students had to the AquaMOOSE system. A few students spent enough time using the system to overcome usability issues and truly engage in personally meaningful constructionist activity, but most of them did not. Likewise, in our comparison class study at a local high school, students followed specific activities during an 8-day curriculum unit designed to teach polar coordinate space. By the end of that curriculum unit, the students had barely gotten comfortable with the AquaMOOSE software tool and had no time left to explore the possibilities it presented. Even in our after-school program study where students used the AquaMOOSE software for a couple hours once a week over an 8-week period, the participants were still exploring different activities within the environment as the study ended. Several students tried new approaches to creating mathematical artworks during the final session of the after-school program, resulting in transformative learning experiences that broadened the students' outlook towards the AquaMOOSE system. Our research indicates that to truly benefit from a constructionist learning environment, participants must be given a significant amount of time to learn the tools as well as to explore the variety of activities that are available to them.

7.1.2 Tradeoffs of Using 3D Technology

The AquaMOOSE project began by leveraging the affordances of a new technology: 3D graphics. This technology presents new opportunities for constructionist learning environments. However, using 3D graphics poses new problems for such systems as well. Through our iterative design and evaluation process, we have begun to understand some of the tradeoffs involved in using 3D graphics to support constructionist learning activities.

7.3.2.1 Visualizing Complex Math

Using 3D graphics allows users to visualize complex math that is not possible to visualize with standard tools. It allows abstract concepts like 3D parametric equations and spherical polar coordinates to become more intuitive. Supporting such epistemological connections is a critical part of a constructionist learning environment. In the GHP study, Mark indicated that he enjoyed using AquaMOOSE better than the normal graphing calculators he had in his math classes: “Most of the time in math classes you don’t have any way to actually represent 3D graphs. Sure, you can do 2D graphs; that’s what the TI-83 is for… AquaMOOSE gave you the chance to do that stuff and had a user-friendly format where you could move around and leave a trail.” However, these new capabilities afforded by using 3D technology also have some drawbacks.

Students using the AquaMOOSE software often had difficulty understanding the 2D representation of a 3D virtual space. As opposed to virtual reality technology, desktop-based 3D environments require a different kind of spatial reasoning than people use in everyday life. This issue is demonstrated most clearly when students try to find a particular view of an artifact they have created in the virtual environment. The students know that the artifact is there, and they know how to move their avatar or camera around in the environment, but they cannot figure out where to position the camera or avatar so that it faces the artifact from the desired angle. This type of disorientation in the virtual space is partially due to the full 3D motion allowed in the AquaMOOSE software. In most other 3D virtual worlds, motion is limited to a 2D plane within the 3D space (such as walking on the ground).

In our second formal evaluation, we administered visual and spatial ability tests to better understand this issue. The results from those tests were inconclusive. Students who scored higher on visual and spatial ability tests did not necessarily understand the AquaMOOSE environment better or perform better on related learning criteria. This issue is one of the most critical concerns for the success of 3D graphical virtual worlds in education. Though we have just begun to understand this issue through our research on the AquaMOOSE software, we hope that continued research in the field could provide design guidelines for helping users better understand this relatively new medium.

Another common difficulty students had in using the AquaMOOSE software was navigating the virtual 3D space. Students in the early evaluations often had difficulty making their avatar move at all, or did not recognize that moving the mouse would change the rotation of their avatar. The navigation scheme we used was based primarily on the controls used in the popular online game EverQuest. We adapted those controls with the hope that our target audience may have experience with that game or other similar games. For many of the students, the similarity to popular game navigation was successful in helping them learn to use the AquaMOOSE software. Students who had no exposure to online games like EverQuest, however, had difficulty understanding how to use both hands (one on the mouse and one on the keyboard) to navigate smoothly through the 3D virtual environment.

In order to address these navigation issues, we experimented with various supports and modifications to help users understand the navigation scheme better. Based on observations of students using the software, we added functionality to the mouse that allowed users to move their avatars forwards and backwards by holding down multiple mouse buttons simultaneously. We also added keyboard shortcuts for moving the avatar along its three major axes (up, down, left, right, forward, and backward). We implemented indicator highlighting within the display area to show that mouse navigation was active. All of these improvements helped alleviate the navigation issues experienced by the students in our more recent evaluations.

Despite these concerns, the new types of complex math made possible by using 3D technology present an opportunity to enhance students' understanding of new mathematical concepts. In keeping with Papert's prediction, it demonstrates an expanded range of easily produced mathematical constructs that can benefit students by promoting a more intuitive understanding of 3D space and related mathematical concepts.

7.1.2.2 Personal Connections to Art

The AquaMOOSE tool was originally designed as a game construction kit where users could create sets of rings in the 3D space and then challenge friends to swim through those rings using parametric equations. During our study at the Georgia Governor's Honors Program (see Chapter IV), Mark described his creations in more artistic terms than we had anticipated. He explained in interviews that he had created "barbed wire" effects and that he wanted to build walls in the 3D virtual space so that he could make tunnels and hallways. This observation prompted us to reconsider the focus of the AquaMOOSE tool.

Instead of participants being mere consumers of the aesthetic appeal of the 3D graphical space, we provided them with more control to create their own aesthetically appealing artifacts. The constructionist philosophy tells us that people are more likely to learn when they are engaged in creating and sharing personally meaningful artifacts. The ability to create 3D artworks is a perfect way to encourage that engagement. However, our desire to provide artistic control to the user needed to be reined in by usability guidelines and careful consideration of the time involved in creating 3D art. It would have been conceivable to incorporate a full 3D modeling tool into the AquaMOOSE environment, allowing users to design and sculpt 3D objects from scratch. While this would have provided complete control over the aesthetic presentation of the virtual space, it would also detract from our focus on combining that artistic expression with mathematics. Our goal in designing the AquaMOOSE system was to provide activities for the participants that facilitate epistemological connections to math, not to create a system where users spent considerable time engaging with graphic design. Instead of a full modeling package, we provided specific artistic manipulations that related to the mathematical trails that are the building blocks in the AquaMOOSE software. Users were given the ability to change the color, width, animation, and smoothness of their trails. They were also given a tool to morph through sequences of mathematical trails similar to some common screensavers. These connections to art provided the students in our evaluations with significant control over the artistic presentation of their work in the 3D environment without overwhelming them with low-level 3D modeling details.

In the final evaluation of the AquaMOOSE system at THS, personal connections to art facilitated by the 3D graphical world are clear. In her “Bunch of Grapes,” Sarah used 3D space to position numerous spherical objects in an approximation of a bunch of grapes. She also added in a green stem to finish off her creation. Tong took advantage of camera placements and avatar positioning to present particular views of his mathematical artifacts in his “Ring of Fire” and “Hypnotize.” Each of these creations, as well as many others created during the THS study, exhibit the personal styles developed by their authors through the use of 3D technology in the AquaMOOSE system to convey particular artistic ideas.

7.1.2.3 Curriculum Goals Versus Technological Capabilities

The 3D technology in the AquaMOOSE system allows students to explore new types of mathematical content that they normally are not exposed to in traditional learning contexts. Rather than being confined by what is covered in a textbook, students using the AquaMOOSE system can experiment with new complex concepts at their own pace. The AquaMOOSE system serves as a middle ground – a stepping-stone where students are able to use knowledge they have gained in the classroom to do things that are well above and beyond what is normally covered in math classes. However, the drawback to that capability is the fact that those new learning activities are not usually a part of standard curriculum goals for math classes.

Most traditional math curriculums do not include 3D mathematical concepts at the high school level. Even in college math classes, 3D concepts are often considered to be advanced and beyond the scope of general courses. The AquaMOOSE system builds on core concepts that are included in standard curriculums, however. Trigonometry and algebra are central to understanding the mathematical activities in the AquaMOOSE system. Polar coordinates are often covered in high school math classes as well, although in 2D rather than 3D. These similarities provide epistemological connections that allow students to get started with the AquaMOOSE system. Once they realize that the math is similar to what they already know, students can build on that experience to explore the new and exciting possibilities that 3D graphical spaces can offer.

7.1.2.4 Scalability

In early versions of our system, clutter was a serious issue. The main activity users engaged in with the AquaMOOSE software was creating mathematical trails. As users created new trails, they often left older trails in the 3D environment. As a result, many of our early users informed us that our virtual fish tank needed to be cleaned often. This problem of virtual clutter was particularly problematic during the stages when we had multiple users sharing the same space. Not only did users have to deal with their own trails taking up room in the environment, but they could easily get confused by what other people were creating as well.

Early online games limited the number of players in a single virtual space in order to alleviate some of the scalability concerns involved with 3D graphical systems. We considered doing the same with the AquaMOOSE project, but we felt that such an artificial limitation would not encourage the type of social interaction that we desired for the system. Instead, we decided to return to a single-user graphical environment where each user's client only rendered his or her avatar and creations in the environment. Social interactions could be supported through a separate, textual interface that would be easier to scale up. In addition, we added easier ways to clear out existing trails and constructed several 3D spaces of varying sizes and shapes to help give users more room to explore and create their artifacts.. Larger environments allowed more flexibility when students were engaging in creative activities, but smaller environments were more visually appealing for exploration and exhibition. This diversity of options seemed to be a reasonable compromise that allowed us to provide usable environments while still leveraging the aesthetic appeal of 3D graphical virtual spaces.

7.2 Concluding Remarks

Over the last seven years, we have used the AquaMOOSE socio-technical system to explore how new technologies like 3D graphical virtual worlds can benefit learning activities. Inspired by Seymour Papert's insights, we began by analyzing the affordances of the technology we chose and then used an evolutionary design process to develop a system that supports a new type of math learning experience. We evaluated that system in different settings and with different learning criteria. We gained insight into the potential uses of this technology, and contemplated the relevance of those insights to other research issues. In this thesis, our seven-year exploration of 3D graphical virtual worlds is presented in the hopes that other researchers can learn from our experiences and continue to expand the range of easily produced mathematical constructs.

This thesis presents a complete story about the design and evaluation of the AquaMOOSE 3D socio-technical system. The AquaMOOSE socio-technical system is driven by the AquaMOOSE software tool, which is described in detail throughout the thesis. Numerous user trials and evaluations were completed to help further the design of the AquaMOOSE system. Those formative evaluations are presented in Chapters III through VI of this thesis.

The AquaMOOSE 3D software was originally envisioned as a platform for carrying out research on how to use 3D graphical virtual worlds for learning. This thesis presents the design of the system and some exploratory results from deploying the system in real educational settings. Many intriguing research questions arose during those evaluations that could spawn future research projects. Though we attempted in our second evaluation to understand why some students understand this type of 3D graphical virtual environment intuitively while others do not, more research could further explain those differences. Through case studies, we also described and analyzed some of the different ways students used the AquaMOOSE system in our final evaluation. Further research could focus on developing more explicit social and technical support for those learning styles. These are only a couple of the possibilities for continuing the exploration we have begun in the AquaMOOSE project.

Developing the AquaMOOSE system has been a challenging but rewarding experience. At times, it seemed as though the point of the project was lost in a fog of low-level design and implementation issues. Particularly in the final evaluation of the system, however, the enthusiasm and diversity of approaches employed by the participants demonstrated that there truly is potential for 3D graphical virtual worlds to positively impact students' learning experiences. After developing and using the software for seven years as a researcher, it was encouraging to see high school students engaging with the system and creating a wide range of interesting mathematical artworks. The AquaMOOSE project has shown that this technology can provide powerful learning experiences that augment standardized educational activities by giving students opportunities to fully employ their imagination and creativity.

APPENDIX A

HANDOUTS

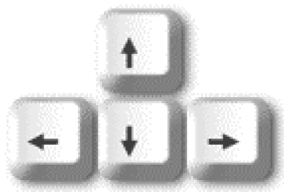
A.1 AquaMOOSE 3D Quick Tips Handout

AquaMOOSE 3D Quick Tips

Basic Navigation:

You may use the arrow keys to move your fish. If you want to change the rotation of your fish, you must use mouse navigation described below.Up arrow key - moves the fish forward

- Down arrow key - moves the fish backward
- Left arrow key - moves the fish to the left
- Right arrow key - moves the fish to the right



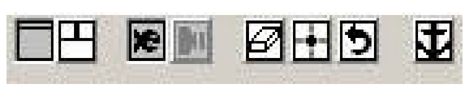
Mouse Navigation:

Point the mouse cursor in the graphical area. You can rotate the fish in all directions while stationary or while moving.

- **Rotate while stationary**
  - o Hold down the right mouse button and
  - o Move mouse – change the rotation of the fish
- **Forward Movement**
  - o Continue to hold the right mouse button
  - o Press left mouse button – move fish forward
- **Reverse Movement**
  - o Continue to hold the right mouse button
  - o Press the middle mouse button – move fish backward

Shortcut Buttons:

The shortcut buttons are One View, Three View, Switch to Avatar Mode, Switch to Camera Mode, Clear Paths, Jump to Origin, Reset View, and Drop Anchor/Pick Up Anchor.



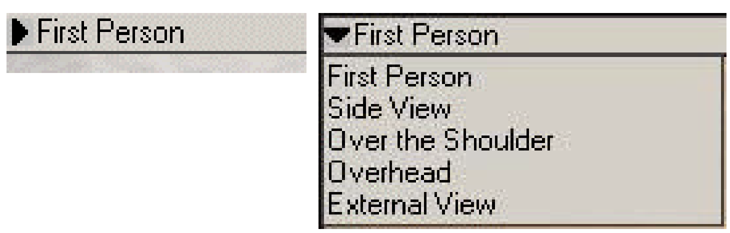
- **One View**
  - o One View is the default setting of the world. It means that there is only one camera view used at a time.
- **Three View**
  - o Three View allows you to use three different camera views at a time. They will automatically go to three separate views, but you can reset them to any view you like. Whatever view you are currently using will become the large, bottom view.

- **Switch to Avatar Mode**
    - Avatar Mode gives you control of your fish.
- **Switch to Camera Mode**
    - Camera Mode gives you control of the external camera. You can only switch to Camera Mode when the External Camera view is on the screen. You can toggle between Avatar Mode and Camera Mode by pressing the End key on the keyboard.
- **Clear Paths**
    - Use Clear Paths to remove old math moves, which speeds up the program and reduces clutter.
- **Jump to Origin**
    - Jump to Origin will move the fish to the origin in the current world.
- **Reset View**
    - Reset View will clear paths, jump to origin, and clear rings.

- **Drop Anchor/Pick Up Anchor**
    - Drop Anchor/Pick up Anchor gives you control over placing the Anchor. If you drop the Anchor, it will be placed at the location of your fish. The Starting Point Absolute button on the Move tab will be automatically selected and the coordinates of the Anchor will be automatically entered as the Absolute coordinates. The next Math Move you perform will start at the location of the Anchor. If you pick up the anchor, it will disappear and the Starting Point coordinates will be the same as they were while the Anchor was down.
      You cannot use the anchor while using Ring Tracks, because all Ring Tracks are centered around the origin.

Camera Angle:

To view your fish from different camera angles, simply click the arrow next to the default setting of First Person.



- **First Person**
    - The camera angle appears as if it is looking out of the fish's eyes.
- **Side View**
    - The camera in this view is looking at the fish from the side.
- **Over the Shoulder**
    - The camera is behind the fish watching it swim with this view.
- **Overhead**
    - The camera is positioned above the fish. If the fish swims straight up, it will face the camera.
- **External View**
    - In this camera view, the camera is detached from the fish and moves all over the world independently.

Functions:

The following are the functions and constants that are available to use in AquaMOOSE.

Function	Symbol	Example
sine	sin( )	x(t) = sin(t)
cosine	cos( )	y(t) = cos(3)
natural log	ln( )	z(t) = ln(t)
power	^	x(t) = t^4
addition	+	y(t) = t + 2
subtraction	-	z(t) = t – 3
multiplication	*	x(t) = t*2
division	/	y(t) = 3/2

Constant	Symbol	Example
3.14 (p)	Pi	x(t) = sin(Pi)
2.718 (e)	e	y(t) = 2*e

A.2 THS Program, Challenge 1: "Circles and Leaves"

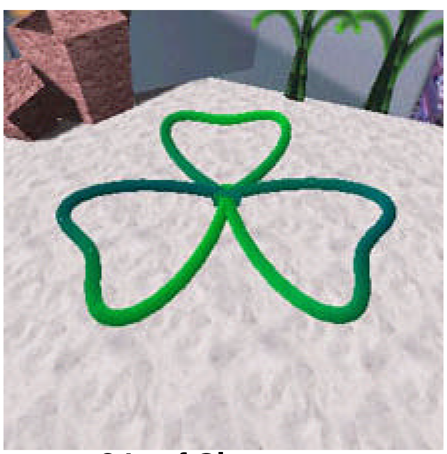
Week One Challenges
Circles and Leaves

One: Add a 4th leaf to this 3 leaf clover.

To create the 3 leaf clover:

1. Click the Reset View button to clear the paths and jump to origin.
2. Enter From t=0 to 2*Pi
3. Select Cylindrical.
4. Enter r(t) = (1 – sin(1.5t)^6) - .1cos(6t).
5. Enter theta(t) = t.
6. Enter z(t) = 0.
7. Click move!

Now see if you can change the equations to add another leaf to that clover!



3 Leaf Clover

Goal

Hints:

Do any of the numbers/variables in the current equation have any relationship to the number three?

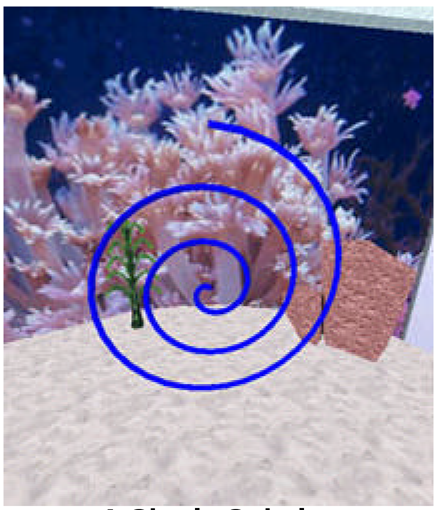
What does changing the numbers in the equation do to the clover?

Two: Create a spiral and display it in the XY, YZ, and XZ planes.

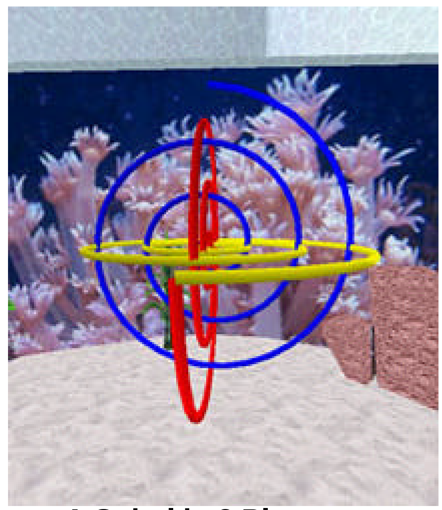
To begin:

1. Click the Reset View button again.
2. By display in the XY, YZ, and XZ planes we mean edit the equations three times so that there is a spiral in each of these planes.
3. You can change the number of layers of the spiral, the size, etc.

First try to make a single spiral and then make one in each plane!



A Single Spiral



A Spiral in 3 Planes

Hints:

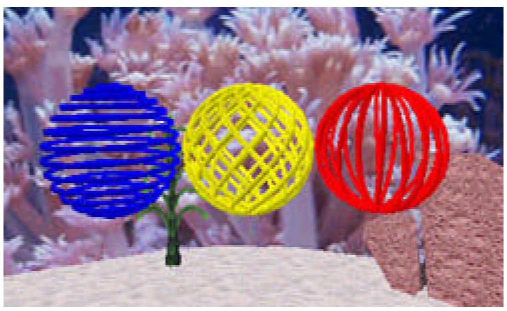
The equation for a spiral is similar to the equation for a circle.

What can you multiply by the circle equation to make a spiral?

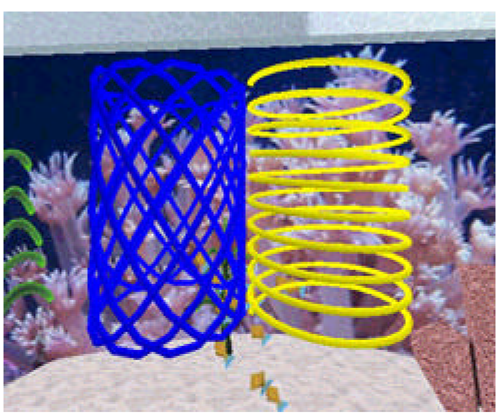
A.3 THS Program, Challenge 2: “Making Spheres: Polar Coordinates”

AquaMOOSE Challenge
Making Spheres: Polar Coordinates

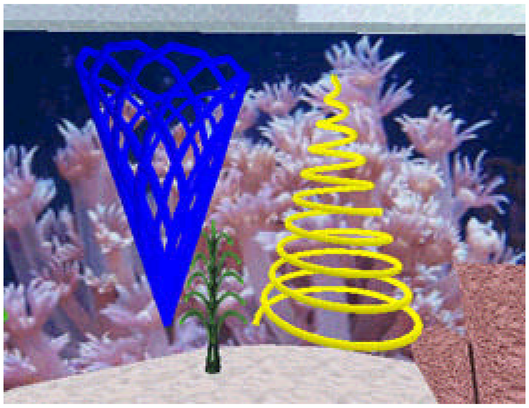
Challenge: Create a Sphere
1. Click the Reset View button.
2. Create a sphere of any size. There are several equations that will result in a sphere.
3. Try manipulating the equation you come up with to change the size (radius) of the sphere.



Challenge: Create a Cylinder
1. Click the Reset View button again.
2. Create a cylinder of any size. Again, there is more than one way to create this shape.
3. Try changing the equations to increase and decrease the height, width, and density of the cylinder.



Challenge: Create a Cone.
1. Click the Reset View button again.
2. Create a cone of any size. Again, there is more than one way to create this shape.
3. Try changing the equations to increase and decrease the height, base, and density of the cone.



Hints:

Are the coefficients for your variables equal? If so, why don't you try making them different?

What is "r" usually in equations pertaining to circles?

For the cylinder, try using the Cartesian plane.

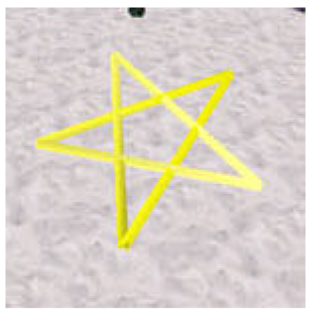
If you change the coefficient for t, what happens to the shape?

A.4 THS Program, Challenge 3: "Trail Properties: Color and Animation"

AquaMOOSE Challenge #4
Trail Properties: Color and Animation

Challenge: **Make a circular trail, and edit its number of segments to make simple geometric shapes.**

1. Make a triangle, a square, and a pentagon.
2. Make a five point star.
3. Make a cylinder shaped like a star.



Challenge: **Make a tornado shaped trail with color properties so that it appears to spiral upward.**

Hint: An equation for a tornado.

1. Select Cartesian.
2. Enter t = 0 to 2*Pi.
3. Enter x(t) = .05*t*t*cos(50t) + .3*cos(50t) + .2*cos(2*t).
4. Enter y(t) = t.
5. Enter z(t) = .05*t*t*sin(50t) + .3*sin(50t) + .2*sin(2*t).

A.5 THS Program, Challenge 4: "Morphing Trail Sequences"

Week Six Challenge
Morphing Trail Sequences

One: Create a caterpillar.
Sine and cosine can be useful for this challenge!

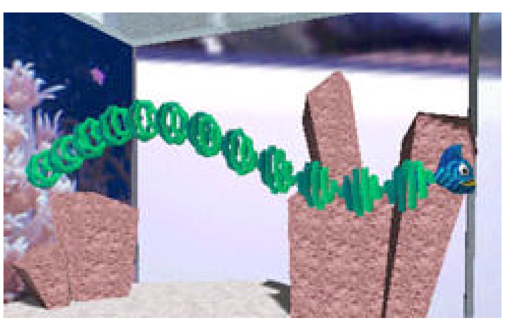
Two: Create a cocoon.
Try using cylindrical coordinate space.
Sine and cosine can be useful for this challenge as well.

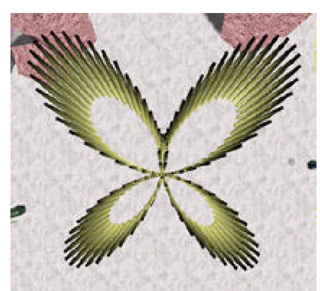
Three: Create a butterfly.
Again, try using cylindrical coordinates.

Four: Create a sequence so that the caterpillar changes into a cocoon, which changes into a butterfly.

You can change the morph and duration times to edit the speed of change and length of time each image appears.

Examples:





Note: Your creations may not look just like these! There are all kinds of different ways that you can create the trails that make up this sequence. Use your imagination!

A.6 THS Program, Artifact Description Document

Participant: ____________________________________

Artifact Name: _________________________________

Date: ____

1. What were your goals for this artifact when you started it?

2. What are you most proud of about this artifact?

3. What was the most fun part of creating this artifact?

4. What was the most frustrating part of creating this artifact?

5. How do you plan to use or change this artifact in the future?

6. What did you learn while building this artifact?

REFERENCES

Barab, S., & Squire, K. (2004). Design-based research: Putting a stake in the ground. *Journal of the Learning Sciences*, *13*(1), 1-14.

Barron, B. J. S., Schwartz, D. L., Vye, N. J., Moore, A., Petrosino, A., Zech, L., et al. (1998). Doing with understanding: Lessons from research on problem- and project-based learning. *Journal of the Learning Sciences, 7*(3&4), 271-311.

Brown, A. (1992). Design experiments: Theoretical and methodological challenges in creating complex interventions. *Journal of the Learning Sciences, 2*, 141-178.

Bruckman, A. (1998). Community support for constructionist learning. *Computer Supported Collaborative Work: The Journal of Collaborative Computing, 7*, 47-86.

Bruckman, A., & Edwards, E. (1999). Should we leverage natural-language knowledge? In *Proceedings of the acm sigchi conference* (pp. 207-214). New York: ACM Press.

Collins, A. (1992). Toward a design science of education. In E. Scanlon & T. O'Shea (Eds.), *New directions in educational technology*. Berlin: Springer-Verlag.

Collins, A., Brown, J. S., & Newman, S. E. (1989). Cognitive apprenticeship: Teaching the crafts of reading, writing, and mathematics. In L. B. Resnick (Ed.), *Knowing, learning, and instruction: Essays in honor of robert glaser*. Hillsdale, NJ: Erlbaum.

Collins, A., Joseph, D., & Bielaczyc, K. (2004). Design research: Theoretical and methodological issues. *The Journal of the Learning Sciences, 13*(1), 15-42.

Conway, M., Audia, S., Burnette, T., Cosgrove, D., Christiansen, K., Deline, R., et al. (2000). Alice: Lessons learned from building a 3d system for novices. In *Proceedings of the acm sigchi conference* (pp. 486-493). Hague, Netherlands: ACM Press.

Dede, C., Salzman, M. C., Loftin, R. B., & Sprague, D. (1999). Multisensory immersion as a modeling environment for learning complex scientific concepts. In W. Feurzeig & N. Roberts (Eds.), *Modeling and simulation in precollege science and mathematics*. USA: Springer Verlag.

Dugdale, S. (1982). Green globs: A microcomputer application for graphing of equations. In *Nctm's mathematics teacher* (pp. 208-214).

Eckstrom, R. B., French, J. W., Harman, H. H., & Derman, D. (1976). Kit of factor-referenced cognitive tests. Princeton, NJ: Educational Testing Service.

Eclipse. (1998). Genesis3d: Open source project. from http://www.genesis3d.com/

Eisenberg, M. (1995). Programmable applications: Interpreter meets interface. *SIGCHI Bulletin, 27*(2), 68-93.

Eisenberg, M., & Nishioka, A. (1997). Creating polyhedral models by computer. *Journal of Computers for Mathematics and Science Teaching, 16*(4), 477-512.

Elliott, J., Adams, L., & Bruckman, A. (2002). *No magic bullet: 3d video games in education.* Paper presented at the International Conference of the Learning Sciences, Seattle, WA.

Elliott, J., & Bruckman, A. (2002). *Design of a 3d interactive math learning environment.* Paper presented at the Design of Interactive Systems, London, UK.

Falbel, A. (1989). *Friskolen 70: An ethnographically informed inquiry into the social context of learning.* Massachusetts Institute of Technology, Boston, MA.

Fennema, E. (1976). Fennema-sherman mathematics attitudes scales. Princeton, NJ: Educational Testing Service.

Fishman, B., Marx, R. W., Blumenfeld, P., Krajcik, J., & Soloway, E. (2004). Creating a framework for research on systemic technology innovations. *Journal of the Learning Sciences, 13*(1), 43-76.

Guzdial, M. (1995). Software-realized scaffolding to facilitate programming for science learning. *Interactive Learning Environments*(4), 1-44.

Harel, I., & Papert, S. (1990). Software design as a learning environment. *Interactive Learning Environments, 1,* 1-32.

Herrmann, T., & Loser, K.-u. (1999). Vagueness in models of socio-technical systems. *Behaviour and Information Technology, 18*(5), 313-323.

Hickey, D., Kindfield, A., Wolfe, E., & Heidenburg, A. (1999). *Genscope evaluation design and learning outcomes.* Paper presented at the National Association for Research in Science Teaching Annual Meeting, Boston, MA.

Joseph, D., & Nacu, D. (2003). Designing interesting learning environments when the medium isn't enough. *Convergence, 9*(2), 84-115.

Kafai, Y., & Harel, I. (1991). Children learning through consulting: When mathematical ideas, knowledge of programming and design, and playful discourse are intertwined. In I. Harel & S. Papert (Eds.), *Constructionism* (pp. 110-140). Norwood, NJ: Ablex Publishing.

Kahle, J., Parker, L., Rennie, L., & Riley, D. (1993). Gender differences in science education: Building a model. *Educational Psychologist, 28,* 379-404.

Ketchum, L., & Trist, E. (1992). *All teams are not created equal: How employee empowerment really works.* Newbury Park, CA: Sage.

Kolodner, J. (2002). Facilitating the learning of design practices: Lessons learned from an inquiry into science education. *Journal of Industrial Teacher Education, 39*(3).

Kolodner, J., Camp, P., Crismond, D., Fasse, B., Gray, J., Holbrook, J., et al. (2003). Problem-based learning meets case-based reasoning in the middle-school science classroom: Putting learning by design into practice. *Journal of the Learning Sciences, 12*(4), 495-547.

Kolodner, J., Crismond, D., Gray, J., Holbrook, J., & Puntambekar, S. (1998). *Learning by design from theory to practice.* Paper presented at the International Conference of the Learning Sciences, Atlanta, GA.

Miller, C. S., Lehman, J. F., & Koedinger, K. R. (1999). Goals and learning in microworlds. *Cognitive Science, 23*(3), 305-336.

Newman, D., Griffin, P., & Cole, M. (1989). *The construction zone: Working for cognitive change in school.* New York: Cambridge University Press.

Norman, D., & Draper, S. (1986). *User centered system design*. Hillsdale, NJ: Lawrence Erlbaum & Associates.

Papert, S. (1980). *Mindstorms: Children, computers, and powerful ideas*. New York: Basic Books.

Papert, S. (1991). Situating constructionism. In I. Harel & S. Papert (Eds.), *Constructionism* (pp. 518). Norwood, NJ: Ablex Publishing.

Piaget, J. (1972). *The principles of genetic epistemology*. New York: Basic Books.

Pintrich, P., & Schunk, D. (1996). *Motivation in education: Theory, research, and applications*. Columbus, Ohio: Prentice Hall.

Ragaini, T. (2000, April 2000). Turbine's asheron's call. *Game Developer,* 54-66.

Resnick, M., Bruckman, A., & Martin, F. (1996, Sept/Oct 1996). Pianos not stereos: Creating computational construction kits. *Interactions, 3*.

Roschelle, J., & Pea, R. (2002). *A walk on the wild side: How wireless handhelds may change cscl.* Paper presented at the Computer Support for Collaborative Learning, Boulder, CO.

Schiefele, U. (1991). Interest, learning, and motivation. *Educational Psychologist, 26*, 299-323.

Soloway, E., Guzdial, M., & Hay, K. (1994). Learner-centered design: The challenge for hci in the 21st century. *Interactions, 1*(2), 36-48.

Tobias, S. (1994). Interest, prior knowledge, and learning. *Review of Educational Research, 64*, 37-54.

Turkle, S., & Papert, S. (1991). Epistemological pluralism and the revaluation of the concrete. In I. Harel & S. Papert (Eds.), *Constructionism.* NJ: Ablex Publishing Corporation.

Verant, I. (2001). Sony online entertainment to introduce new everquest servers in european markets. from http://www.verant.com/press_releases.html

Wertsch, J. (1986). *Vygotsky and the social formation of mind*. Cambridge, MA: Harvard University Press.

Wigfield, A. (1994). Expectancy-value theory of achievement motivation: A developmental perspective. *Educational Psychology Review, 6*, 49-78.

Wigfield, A., & Eccles, J. (1992). The development of achievement task values: A theoretical analysis. *Developmental Review, 12*, 265-310.

Yee, N. (2001). The norrathian scrolls: A study of everquest (version 2.5). from http://www.nickyee.com/eqt/report.html

Zagal, J., & Bruckman, A. (2005). From samba schools to computer clubhouses: Cultural institutions as learning environments. *Convergence, 11*(1), 88-105.

VITA

Jason Lynn Elliott was born on December 9, 1974 in Sanford, North Carolina. He graduated as Valedictorian from Lee County High School in 1993 and began his undergraduate studies at North Carolina State University in Raleigh, North Carolina. He graduated as Valedictorian from North Carolina State University in 1997 with his B.S. degree in Computer Science. He then began his graduate studies at the Georgia Institute of Technology in Atlanta, Georgia as a National Science Foundation Trainee with the Graphics, Visualization, and Usability Center. Jason worked for Nortel Networks in Research Triangle Park, North Carolina during the first three summers of his graduate studies. In the summer of 2000, he worked with Wendy Kellogg in the Social Computing Group at IBM's T.J. Watson Research Lab in Hawthorne, New York. During his studies under Dr. Amy Bruckman at the Georgia Institute of Technology, Jason developed and evaluated the AquaMOOSE 3D system, which is a 3D graphical constructionist learning environment designed to engage students in learning new mathematical concepts by supporting artistic creativity. His thesis describes the AquaMOOSE system and implications derived from three user studies conducted in various real-world learning contexts. Jason earned his M.S. degree in Computer Science from the Georgia Institute of Technology in 2001. He then completed his thesis and received his Ph.D. in Computer Science from the Georgia Institute of Technology in 2005.